

Breit–Pauli energy levels, transition probabilities and lifetimes for $3d^5$ levels in Fe IV of astrophysical interest

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Accepted 2004 August 18. Received 2004 August 17; in original form 2004 June 3

ABSTRACT

Energy levels, lifetimes and transition probabilities for transitions between computed levels of $3d^5$ of Fe IV are reported. The E2 and M1 transition probabilities are compared with earlier theoretical results, often only the values published by Garstang in 1958. From the available astronomical observations of optical emission lines arising from the same level, a few direct tests are now possible and they show consistency with the theoretical calculations.

Key words: atomic data – atomic processes.

1 INTRODUCTION

Triply ionized iron Fe^{3+} is expected to be a significant fraction of gaseous iron in many nebulae. Indeed, Fe^{3+} may be the dominant ionic state of Fe in many nebulae, including H II regions and planetary nebulae (PNs). For instance, in two independent photoionization models of the benchmark Orion Nebula, the fractional ionization $\langle \text{Fe}^{3+} \rangle$ was predicted to be 0.744 by Baldwin et al. (1991a, and 0.533 by Rubin et al. (1991a,b). Naturally, in order to get a grip on iron abundances, it is important to treat the dominant ionic component. To interpret observations of emission lines of [Fe IV], it is necessary to have reliable atomic data, including effective collision strengths (Fe^{3+} with electrons) and transition probabilities (Einstein A-values). These atomic data are important for interpreting astronomical observations over a wide spectral range from the ultraviolet to the infrared.

In our earlier paper (Froese Fischer & Rubin 1998), we provided A-values for transitions between the 12-lowest energy levels. Effective collision strengths had just become available for these 12-lowest levels (Berrington & Pelan 1995, 1996). Although there were A-values available from Garstang (1958), improvements in the state-of-the-art made it worthwhile to recalculate a complementary set that would permit a solution for the detailed population statistical equilibrium for the 12-level atom. This depends on the electron density (N_e) and electron temperature (T_e).

One of the motivating factors in our 1998 paper was to provide improved A-values for a set of transitions involved in the determination of the intensity of the UV [Fe IV] 2836.56-Å line measured with the *Hubble Space Telescope* (HST) in the Orion Nebula by Rubin et al. (1997) – the first detection of an [Fe IV] line in an H II region. They had measured the flux of [Fe IV] ($3d^5\ 4P_{5/2} \rightarrow 3d^5$

$^6S_{5/2}$) $\lambda_{\text{vac}} = 2836.56$ Å and set an upper limit on the sum of fluxes of [Fe IV] ($3d^5\ 4D_{5/2,3/2} \rightarrow 3d^5\ ^6S_{5/2}$) $\lambda_{\text{vac}} = 2568.4$, 2568.2 Å.

Unfortunately, Fe^{3+} does not have intrinsically bright lines under nebular conditions. Recently there have been measurements of some optical lines of [Fe IV] (e.g. Rodríguez 2003). Rodríguez found for five nebulae that the Fe^{3+} abundance derived from observations of [Fe IV] lines was systematically lower than expected. This is in the same direction as found earlier by Rubin et al. (1997) for the Orion Nebula.

In their study of the bipolar PN Mz 3, Zhang & Liu (2002) measured five optical [Fe IV] lines as well as several lines of [Fe III]. They found evidence for high N_e in the Fe^{++} region of $\log N_e(\text{cm}^{-3}) = 6.5$. They also suggested that N_e in the central emitting core could be even higher. An interpretation of those data would benefit from improved A-values, particularly when dealing with higher-density gas where the statistical equilibrium for the energy level populations depends critically on the transition rates.

Most, if not all, of the optical [Fe IV] lines observed astronomically arise from energy levels above the 12-lowest levels for which we calculated A-values (Froese Fischer & Rubin 1998). These optical (as well as infrared) lines originate from energy levels above the 4D -levels (beginning with level 13).

Zhang & Pradhan (1997) extended the calculation for [Fe IV] effective collision strengths to a 140-level atom (49 terms up to 15 Ryd; 1 Ryd = 2.180×10^{-18} J). Because of the availability of these data and the need to consider higher levels to interpret/predict most of the [Fe IV] lines that are being observed, we are making these new, improved A-value computations including 16 terms, which comprise the 37 lowest-lying energy levels (below 1 Ryd).

The goal of our earlier publication was to predict transition probabilities in emission from $3d^5\ ^4G$, 4P and 4D to the $^6S_{5/2}$ ground state. In the process, transition probabilities were also computed for transitions between the levels of the 4L terms. Four theoretical methods were compared and best estimates were identified. Frequently

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these were the multiconfiguration Hartree–Fock with Breit–Pauli (MCHF+BP) results, although not always. The multiconfiguration Dirac–Hartree–Fock with the Breit (MCDHF+B) correction was selected in some cases for magnetic dipole (M1) transitions. In a few instances, a semi-empirical method based on orthogonal operator techniques (Raassen & Uylings 1996) was selected. In this paper we extend the Breit–Pauli work to include all levels of the $3d^5$ configuration up to 1 Ryd.

2 COMPUTATIONAL PROCEDURE

In the Breit–Pauli approximation, the wave function, Ψ , is a linear combination of configuration state functions (CSF) of the form

$$\Psi(\gamma J) = \sum_{LS} \sum_j c_j(LSJ) \Phi(\gamma_j LSJ), \quad (1)$$

where γ usually represents the dominant configuration and any additional quantum numbers required for uniquely specifying the state. The CSFs, $\Phi(\gamma_j LSJ)$, for a configuration and coupling γ_j , the term LS , and the total angular momenta L and S coupled to J are built from a basis of one-electron spin orbitals

$$\phi_{nlm_lm_s} = \frac{1}{r} P_{nl}(r) Y_{lm_l}(\theta, \varphi) \chi_{m_s}. \quad (2)$$

The expansion coefficients, $c_j(LSJ)$, and the corresponding energy, $E(LSJ)$, are an eigenvector and eigenvalue, respectively, of the interaction matrix of these CSFs as defined by the Breit–Pauli Hamiltonian. The evaluation of the matrix elements is considerably simplified if the spin orbitals are orthonormal, which means that, for a given l , the radial functions $P_{nl}(r)$ must be orthonormal, and that the same radial functions must be used to represent the different terms.

In this approximation, the configuration states in the expansion and the spin orbitals are determined from non-relativistic calculations. The multiconfiguration Hartree–Fock (MCHF) method was used for this purpose, extended to obtain the ‘best’ radial functions for the set of LS terms. In all the present work, $1s^2 2s^2 2p^6$ was considered an inactive core.

Typically, the different terms of a configuration that interact through relativistic operators for one or more J values are grouped and the radial functions optimized for the group. However, many of the transitions among the levels of $3d^5$ are spin-forbidden. These transitions arise from small admixtures of quartet components to doublet levels and vice versa. Thus even small admixtures require terms to be in the same group. What compounds the difficulty in this case is the fact that the 5^2D CSF interacts strongly through a coulomb interaction with the 1^2D CSF. (In this notation, the subscript preceding the LS term is the seniority of the term. We will include seniority only when it is necessary to distinguish different terms.) The former is the dominant component of a term low in the spectrum, whereas the latter is a dominant component for a term high in the spectrum. At the same time, the 4^F and 3^2F CSF interacted strongly through the relativistic operators, as did others. In order not to miss small relativistic interactions, it was decided to include all levels in one group, but omit optimization of orbitals for the ground state which contains considerably less correlation than the other levels.

With this in mind, a multireference set was created for each term that included the $3p \rightarrow 4p$ and $3d \rightarrow 4d$ replacements from $3s^2 3p^6 3d^5$ to allow for term dependence of the $3p$ and $3d$ orbitals. Calculations were performed with orbital sets of increasing size with the $n = 4$ orbital set, including all occupied orbits as well as $4s, 4p, 4d$ and $4f$. The $n = 4$ expansion for a given term was obtained through single (S) and double (D) excitations from the multireference set to the $n = 4$ orbital set. For $n = 5, 6, 7$, the $3s$ shell was

kept inactive, and SD excitations with at most one excitation from the $3p^6$ subshell were added to the $n = 4$ expansion. Given that each of these expansions was fairly long and that there were 13 terms, it was necessary to eliminate the small contributors to an LS expansion. MCHF calculations were performed for each LS term and expansions condensed, in that CSFs with an expansion coefficient less than 0.000 01 were eliminated. Once these expansions had been obtained, simultaneous optimization was performed for all 12 terms (omitting 6^S) to obtain radial functions.

Once the radial basis had been determined, the Breit–Pauli interaction matrix was determined including all LS terms. The results define our ab initio energies.

When observed energy level data are available, transition probabilities, A_{ki} , can be improved by various energy adjustments. The first such adjustment is one that corrects for the transition energy. Let $r = \Delta E_{\text{obs}} / \Delta E_{\text{calc}}$. Then $A_{ki}(\text{adj}) = r^m A_{ki}(\text{calc})$, where $m = 3$ for M1 transitions and $m = 5$ for electric quadrupole (E2) transitions. This adjustment is the most straightforward, but for Breit–Pauli calculations where we have the mixing of different LS terms, this mixing itself is affected by the ‘term energy separation’. Although it is possible, in simple cases, to correct a computed A_{ki} for such an error, it is simpler to first adjust the LS term energies in a Breit–Pauli calculation so that, for selected J values, the separation of terms is in close agreement with that observed. Typically, this is done by first determining energies without an adjustment, noting the deviation from observed for the J values of different terms, selecting a J value from each term for adjusting all levels of a term, and then modifying the diagonal energies of all CSFs associated with a given LS by this amount. Unless selected J values are exceedingly close, just one such iteration brings energies into close agreement with those observed. It usually does not change the ‘spread’ of a term, the difference in energy between the highest and lowest level of a term. However, $3d^5$ being a half-filled shell, there is no diagonal spin-orbit interaction and fine-structure splitting is more complex. We refer to calculations where only the diagonal energies have been changed as ‘adjusted’. Because there are as many as three terms with the same LS value, as for the 2^D terms (5^2D , 3^2D and 1^2D , where the preceding subscript is the seniority), the adjustments were done in groups in order of energy:

- (1) $6^S - 4^F$;
- (2) $3^2H - 5^2F$;
- (3) $2^S - 3^2D$; and
- (4) $3^2G - 1^2D$.

Table 1 reports the final spectrum, the splitting relative to the lowest level of the LS term, and the difference with the observed [National Institute of Standards and Technology (NIST) Atomic Spectra Database, Physical Reference Data; <http://physics.nist.gov>]. Because the adjustment involves only one J level of a term, not all levels are in close agreement with those observed. The largest deviation from the observed spectrum was 115 cm^{-1} in an excitation energy of $50\,051 \text{ cm}^{-1}$.

3 ANALYSIS OF ENERGY LEVELS

Although the differences in our energies relative to observed are not large, they do indicate that the fine-structure splitting has not been determined accurately. If a term is simply shifted relative to the ground state, then the difference with observed should be essentially constant. In the quartet terms, the levels are not always in the correct order. For example, the observed order of levels of 4^G is $(11/2, 9/2, 5/2, 7/2)$ and the present order is $(11/2, 5/2, 7/2, 9/2)$, whereas the

Table 1. Energy levels, their splitting, difference from observed [computed – observed (NIST)], lifetimes and composition of the $3d^5$ levels.

LS	J	Level (cm^{-1})	Split.	Diff.	τ (s)	Composition (per cent)
6S	5/2	0				96
4G	11/2	32245.54		0.04		96
	5/2	32260.47	14.92	-40.73	4.653e+04	96
	7/2	32300.52	54.98	-5.18	3.492e+05	96
	9/2	32307.06	61.52	14.26	1.216e+05	96
4P	5/2	35229.91		-23.87	6.408e-01	$91 + 4^4D$
	3/2	35362.69	132.78	29.39	9.803e-01	$92 + 3^4D$
	1/2	35399.47	169.56	-7.13	4.177e+05	$95 + 1^4D$
4D	7/2	38778.87		-0.53	1.955e+01	95
	1/2	38918.56	139.69	21.86	8.541e+00	$95 + 1^4P$
	5/2	38968.60	189.73	33.50	9.896e+00	$91 + 4^4P$
	3/2	38973.28	194.41	2.68	9.395e+00	$92 + 3^4P$
2I	11/2	47081.28		73.74	1.014e+02	95
	13/2	47164.24	82.96	42.34	3.280e+03	96
$^5^2D$	5/2	49583.84		114.59	9.332e-01	$52 + 25_3^2F + 19_1^2D$
	3/2	50165.99	582.15	1.25	2.145e+00	$69 + 22_1^2D + 5^4F$
$^3^2F$	7/2	51395.45		65.84	1.211e+00	$92 + 1^4F + 1_5^2F$
	5/2	52232.54	837.09	-9.06	1.085e+00	$60 + 18^4F + 13_5^2D + 4_1^2D$
4F	9/2	52611.64		-9.06	1.432e+00	$94 + 2^2G$
	7/2	52712.37	100.74	16.97	1.464e+00	$93 + 1_3^2F$
	5/2	52893.99	282.35	55.99	1.071e+00	$76 + 10_3^2F + 7_5^2D + 2_1^2D$
	3/2	52894.38	282.75	57.28	1.219e+00	$91 + 4_5^2D$
2H	9/2	56093.94		35.64	1.992e+00	$79 + 16^2G$
	11/2	56421.86	327.91	53.06	9.092e-01	95
$^5^2G$	7/2	57411.28		3.28	1.138e+01	95
	9/2	57743.98	332.70	22.78	4.590e+00	$78 + 17_3^2H + 1^4F$
$^5^2F$	5/2	61129.72		-26.78	3.790e+00	95
	7/2	61258.00	128.28	3.60	3.502e+00	$94 + 1_3^2F$
2S	1/2	66720.76		0.66	1.024e+00	95
$^3^2D$	3/2	74098.16		1.56	6.529e-01	95
	5/2	74147.52	49.36	14.42	5.050e-01	95
$^3^2G$	9/2	82895.92		1.02	1.543e-01	95
	7/2	82943.02	47.10	45.72	1.458e-01	95
2P	3/2	100118.46		0.46	4.620e-02	95
	1/2	100119.61	1.14	-6.34	4.512e-02	95
$^1^2D$	5/2	108220.14		-21.96	5.295e-02	$72 + 23_5^2D$
	3/2	108263.47	43.32	5.17	5.266e-02	$72 + 23_5^2D$

order in the semi-empirical work of Garstang (1958) was (5/2, 7/2, 9/2). All levels are close together, with the observed spread being only $\sim 60 \text{ cm}^{-1}$. However, the splitting within a multiplet is only important for the transitions within a multiplet, determining the order and the wavelength. The length form of the linestrength (S) is largely independent of the energy.

Table 1 shows that the wave functions for many levels have a composition that includes a number of LS terms at the 1 per cent level. The first number is the percentage composition of the dominant CSF. Many are listed as 95–96 per cent. The remaining composition represents correlation effects and small relativistic interactions. However, some levels have a highly mixed composition and the accuracy of transition probabilities, particularly spin-forbidden transitions, from such levels depends on how well the composition of the wave function is represented. The accuracy of this mixing can be assessed to some extent by the accuracy of the spectrum for a particular J and the separation between levels. An important value is $J = 5/2$ and in Table 2 these energy levels are listed along with the separation of a particular level from the previous one. The present adjusted energy separations are compared with observed separations and those derived by Garstang (1958). Considering the incomplete

identification of the spectrum at the time of Garstang's work, his results are remarkable. Table 2 shows immediately that a potentially strong mixing of the $^3^2F$ and 4F configuration states may occur for $J = 5/2$, with a separation of only 671 cm^{-1} between the energies of these two terms. This separation has been reproduced with an error 1.5 per cent, although it needs to be remembered that these are adjusted values. The ab initio separation was 894 cm^{-1} .

Close levels of the same J value are sensitive to the separation and so this can be used as a test for accuracy, but strong mixing can also occur simply because of a large off-diagonal matrix element in the Breit–Pauli Hamiltonian. In Table 1, we note the strong mixing of the 4F term with the nearby $^3^2F$ term for $J = 5/2$, but the strongest mixing is between $^5^2D$ and $^3^2F$ for $J = 5/2$, although this separation is larger.

4 COMPARISON OF CALCULATED TRANSITION PROBABILITIES

The complete set of transition probabilities between all the levels of our energy adjusted data can be found at <http://atoms.vuse.vanderbilt.edu>. Transition probabilities between

Table 2. Comparison of $J = 5/2$ level separation, in cm^{-1} .

Term	Level	Obs.	Separation Garstang	Present
6S	0			
4G	32301	32301	32213	32260
4P	35254	2953	2882	2969
4D	38935	3681	3372	3739
$^5^2D$	49542	10606	10636	10615
$^3^2F$	52167	2625	2760	2649
4F	52838	671	688	661
$^5^2F$	61157	8319	7764	8235
$^3^2D$	74133	12977	12919	13018
$^1^2D$	108242	34109	33744	34073

many levels are reported in the Appendix with the wavelengths corrected to agree with those observed, and the A_{ki} are modified accordingly. The Appendix is available as a machine-readable table in the electronic edition at <http://www.blackwellpublishing.com/products/journals/suppmat/MNR/MNR8332/MNR8332sm.htm>.

In order to assess the accuracy of these results, we compare the present transition probabilities between the 6S , 4P and 4D terms for which our previous publication had compared four different theoretical approaches: Garstang's 1958 calculations, the semi-empirical orthogonal operator method (Raassen & Uylings 1996), an MCHF+BP method and an MCDHF+B method, and the most reliable value identified. E2 transition probabilities are compared in Table 3 and M1 transition probabilities are compared in Table 4. Although our previous calculations were not as ambitious as the present, MCHF+BP was often identified as the most reliable; however, MCDHF+B was selected for some M1 transitions and the results by Raassen & Uylings (1996) were selected for some E2 transitions. The present results are often similar to the earlier ones, but some small values are now closer to those of Raassen & Uylings, possibly because more term mixing was taken into account. An example is the $^6S_{5/2} - ^4G_{7/2}$ E2 value which previously was computed to have a transition probability of 5.27×10^{-12} has now become 3.32×10^{-8} . The latter is in excellent agreement with the orthogonal operator value of 3.18×10^{-8} that fortuitously had been selected as the most reliable.

Table 3. Comparison of normalized E2 transition rates $A_{J'J}$ (in s^{-1}) in emission for different theories: (1) from Garstang (1958), (2) from Raassen & Uylings (private communication, 1997), MCHF+BP and MCDHF+B (Froese Fischer & Rubin 1998) and the present theory (asterisks denote the previously recommended value). Here, as well as in Tables 4 and 5, the part of the numerical entries in parentheses denotes the exponent of 10.

LS	$L'S'$	J	J'	Obs. E (cm^{-1})	Semi-empirical (1)	Semi-empirical (2)	MCHF+BP	MCDHF+B	present
4G	4P	7/2	5/2	2948.0	2.3(-09)	3.42(-09)*	5.90(-13)	1.01(-18)	3.68(-09)
		5/2	5/2	2952.8	1.4(-09)	1.83(-09)*	1.01(-13)	6.99(-08)	1.86(-09)
		9/2	5/2	2961.0	6.4(-10)	1.75(-10)*	2.63(-11)	5.83(-08)	7.50(-10)
		7/2	3/2	3027.0	1.3(-09)	6.22(-10)*	4.61(-11)	1.07(-08)	1.60(-09)
		5/2	3/2	3031.8	8.5(-10)	1.34(-09)*	6.89(-12)	7.38(-08)	1.30(-09)
	4D	1/2		3105.8	3.4(-10)	9.79(-11)*	2.91(-11)	1.21(-06)	4.02(-10)
		3/2	7/2	3446.0	2.9(-06)	4.65(-06)	4.73(-06)*	3.06(-09)	4.97(-06)
		5/2	7/2	3525.0	4.9(-06)	7.65(-06)	8.02(-06)*	3.16(-09)	8.41(-06)
		1/2	5/2	3528.0	3.1(-06)	5.08(-06)	4.98(-06)*	1.26(-07)	5.21(-06)
		3/2	5/2	3531.0	1.8(-06)	3.04(-06)	2.98(-06)*	3.19(-07)	3.01(-06)
4P	4D	3/2	1/2	3564.0	6.9(-06)	1.23(-05)	1.15(-05)*	9.70(-08)	1.17(-05)
		5/2	5/2	3602.0	1.5(-07)	2.26(-07)	2.13(-07)*	5.22(-07)	2.46(-07)
		3/2	3/2	3605.0	3.3(-06)	5.45(-06)	5.17(-06)*	2.04(-06)	5.52(-06)
		5/2	1/2	3643.0	9.9(-07)	1.65(-06)	1.68(-06)*	1.53(-07)	1.64(-06)
		5/2	5/2	3681.0	5.5(-06)	8.64(-06)	8.59(-06)*	7.11(-06)	9.17(-06)
		3/2	3/2	3684.0	3.4(-06)	5.65(-06)	5.48(-06)*	4.20(-07)	5.60(-06)
		7/2	7/2	6473.0	6.8(-07)	1.17(-06)	3.62(-10)*	4.97(-07)	1.11(-06)
		5/2	7/2	6477.8	5.2(-08)	8.29(-08)	6.45(-11)*	3.48(-08)	7.42(-08)
		9/2	7/2	6486.0	1.5(-06)	2.85(-06)	2.61(-09)*	1.49(-06)	2.77(-06)
		11/2	7/2	6533.5	1.7(-07)	2.96(-10)	1.75(-08)*	1.20(-06)	2.59(-07)
4G	4D	5/2	1/2	6595.8	1.0(-07)	2.84(-08)	1.67(-08)*	1.56(-06)	1.21(-07)
		7/2	5/2	6629.0	1.1(-06)	2.28(-06)	4.31(-09)*	4.91(-07)	1.99(-06)
		3/2	3/2	6632.0	6.0(-07)	2.08(-07)	1.26(-08)*	1.03(-07)	9.19(-07)
		5/2	5/2	6633.8	7.2(-07)	1.28(-06)	4.84(-10)*	1.07(-07)	1.20(-06)
		3/2	3/2	6636.8	6.6(-07)	1.52(-06)	4.95(-09)*	2.21(-07)	1.16(-06)
		9/2	5/2	6642.0	6.7(-07)	2.76(-07)	1.43(-08)*	8.83(-07)	1.09(-06)
		5/2	9/2	32293.0	<1.0(-09)	6.92(-12)*	1.32(-09)	1.27(-05)	1.85(-09)
		5/2	5/2	32301.2	<1.0(-09)	1.95(-08)*	4.07(-11)	6.09(-05)	2.30(-08)
		7/2		32306.0	<1.0(-09)	3.18(-08)*	5.72(-12)	1.10(-05)	3.32(-08)
		4/2	5/2	35254.0	3.9(-05)	4.26(-05)	3.10(-05)*	4.01(-03)	4.02(-05)
4P	4D	3/2		35333.0	1.5(-05)	1.99(-05)	8.84(-06)*	5.83(-01)	1.21(-05)
		1/2		35407.0	v.s.	1.67(-06)	2.10(-07)*	1.28(00)	1.47(-07)
		7/2		38779.0	1.1(-03)	1.13(-03)	1.18(-03)*	4.40(-04)	1.27(-03)
		1/2		38897.0	1.8(-04)	1.97(-04)	2.03(-04)*	1.58(-02)	2.17(-04)
		5/2		38935.0	1.0(-03)	1.09(-03)	1.15(-03)*	1.58(-03)	1.23(-03)
6S	4G	3/2		38938.0	6.2(-04)	6.72(-04)	6.86(-04)*	2.64(-02)	7.33(-04)

Note: v.s. means very small in Garstang (1958) compilation.

Table 4. Comparison of normalized M1 transition rates $A_{J'J}$ (in s^{-1}) in emission for different theories: (1) from Garstang (1958), (2) from Raassen & Uylings (private communication, 1997), MCHF+BP and MCDHF+B (Froese Fischer & Rubin 1998) and the present theory (asterisks denote the previously recommended value). Here, as well as in Tables 4 and 5, the part of the numerical entries in parentheses denotes the exponent of 10.

LS	$L'S'$	J	J'	Obs. E (cm^{-1})	Semi-empirical (1)	MCHF+BP	MCDHF+B	present
4G	4P	7/2	5/2	2948.0	1.5(-05)	1.89(-05)	8.02(-08)	1.51(-05)*
		5/2	5/2	2952.8	6.8(-05)	1.04(-04)	7.36(-07)	7.90(-05)*
		5/2	3/2	3031.8	8.6(-06)	1.33(-05)	1.21(-07)	9.79(-06)*
4P	4D	1/2	1/2	3490.0	5.8(-02)	6.51(-02)	6.04(-02)*	4.94(-02)
		5/2	7/2	3525.0	3.8(-02)	4.26(-02)	3.86(-02)*	3.31(-02)
		1/2	3/2	3531.0	1.4(-03)	1.89(-03)	1.70(-03)*	1.48(-03)
		3/2	1/2	3564.0	3.4(-02)	4.00(-02)	3.67(-02)*	3.08(-02)
		5/2	5/2	3602.0	3.5(-03)	3.74(-03)	3.59(-03)*	2.92(-03)
		3/2	3/2	3605.0	3.9(-02)	4.30(-02)	3.97(-02)*	3.32(-02)
		5/2	5/2	3681.0	2.2(-02)	2.46(-02)	2.26(-02)*	1.92(-02)
		3/2	3/2	3684.0	1.8(-02)	2.06(-02)	1.83(-02)*	1.61(-02)
		7/2	7/2	6473.0	7.6(-04)	1.10(-03)	2.12(-05)	8.29(-04)*
4G	4D	5/2	7/2	6477.8	7.6(-05)	1.08(-04)	2.18(-06)	8.18(-05)*
		9/2	7/2	6486.0	6.3(-04)	9.02(-04)	1.46(-05)	6.89(-04)*
		7/2	5/2	6629.0	v.s.	2.51(-08)	6.29(-09)	2.66(-04)*
		5/2	5/2	6633.8	5.8(-04)	8.64(-04)	1.90(-05)	6.82(-04)*
		3/2	3/2	6636.8	2.8(-04)	3.69(-04)	7.92(-06)	2.82(-04)*
6S	4G	5/2	5/2	32301.2	1.0(-05)	1.53(-05)	8.78(-08)	1.01(-05)*
		7/2	7/2	32306.0	<1.0(-07)	3.78(-08)	5.28(-10)	1.42(-08)*
4P	4D	5/2	5/2	35254.0	1.4	1.42	1.53*	1.17
		3/2	3/2	35333.0	8.8(-01)	9.23(-01)	9.98(-01)*	7.59(-01)
4D	4D	7/2	7/2	38779.0	2.0(-04)	5.90(-04)	7.18(-04)*	2.44(-04)
		5/2	5/2	38935.0	5.1(-02)	5.69(-02)	5.32(-02)*	3.40(-02)
		3/2	3/2	38938.0	3.8(-02)	2.75(-02)	2.61(-02)*	1.65(-02)

Note: v.s. means very small in Garstang (1958) compilation.

For the transition probabilities for the newly included terms, the only other values are those reported by Garstang (1958) in his table III, but only up to level 33. In Table 5 we present only those multiplets arising from higher levels than those shown in Tables 3 and 4 and that give rise to an optical emission line that may possibly have been seen astronomically. As shown in Table 5, for spin-allowed transitions, some results are in excellent agreement with the Garstang values. There are five transitions for which very small A_{ki} values (no larger than $3.41 \times 10^{-14} \text{ s}^{-1}$) are given in Garstang (1958) but not in the Appendix. We calculate that all of these are now less than $5.3 \times 10^{-14} \text{ s}^{-1}$ and negligible. These or other transitions not listed in the Appendix are available from <http://atoms.vuse.vanderbilt.edu>. Again, the web site values have not been adjusted to observed wavelengths, and the steps mentioned in Section 2 should be followed to modify A_{ki} .

In conclusion, by including the Breit–Pauli interactions between all the terms of $3d^5$, the calculations are more complete. Some E2 transition probabilities for transitions among the four lowest terms remain similar but others have come closer to semi-empirical values. An example is the ${}^4G - {}^4P$ multiplet.

5 COMPARISON WITH OBSERVATIONS

Because of the inherent faintness of the [Fe IV] lines, there is as yet very little data for a ‘direct’ test of the A -values. One astronomical object that permits such a test is RR Telescopii, which is a symbiotic nova (e.g. McKenna et al. 1997). In table 1 of their paper, they have observations of two emission lines arising on the same level, for each of two different upper levels. All are within the ${}^4F \rightarrow {}^4G$

multiplet. The first test is the intensity ratio of the 4903.07-Å line to the 4899.97-Å line (rest-air wavelengths from NIST). (These are listed somewhat differently in the McKenna et al. table as 4903.50 and 4900.05 Å.) These are respectively ${}^4F_{7/2} \rightarrow {}^4G_{7/2,9/2}$. To facilitate comparison with the theoretical transition probabilities in our tables, the vacuum wavelengths for these lines are 4904.44 and 4901.34 Å, respectively.

The predicted line intensity ratio $I(4903)/I(4900)$ is simply the ratio of the products of the line frequency and the A -value, where the A -value is the sum of E2 and M1. According to the Appendix, the present predicted ratio is 1.10 which is close to that predicted by Garstang (1958) of 1.04. The observed ratio from McKenna et al. (1997) is 1.13, where $F(4903) = 4.4$ and $F(4900) = 3.9$ in units of $10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$.

The second pair of observed lines in RR Tel permits a test of the intensity ratio $I(4907)/I(4918)$. The best (NIST) rest-air wavelengths are 4906.56 and 4917.98 Å (these are listed somewhat differently in the McKenna et al. table as 4906.70 and 4918.10 Å) and are respectively ${}^4F_{9/2} \rightarrow {}^4G_{11/2,9/2}$ with vacuum wavelengths of 4907.93 and 4919.35 Å. The present predicted line intensity ratio $I(4907)/I(4918)$ from the Appendix is 3.17, whereas the ratio from Garstang (1958) is 2.72. The observed ratio from McKenna et al. (1997) is 2.39, where $F(4907) = 9.1$ and $F(4918) = 3.8 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$. However, this comparison does not account for a possible contribution of an Fe III line at 4918.00 Å, also listed as a possible identification along with the [Fe IV] line for their observed feature at 4918.04 Å (McKenna et al. 1997). That would lower both of the above predicted ratios by some undetermined amount.

For one of the PNs that Liu et al. (2004) observed, NGC 6884, two emission lines of [Fe iv] from the same upper level are listed in their table 3. These are the same pair of lines as was discussed above in the first instance for RR Tel. However, for NGC 6884, they also list a line due to [Fe vi] at 4903.30 Å as a possible identification for

Table 5. Comparison with the Garstang (1958) values of some A_{ki} for E2 and M1 transitions between higher levels.

Multiplet	g_i	g_k	E2		M1	
			Present	Garstang	Present	Garstang
$^4G - ^2I$	8	12	1.14(−06)	1.0(−06)		
	10	12	2.61(−06)	3.3(−07)	2.32(−03)	3.0(−03)
	10	14	8.81(−07)	1.6(−06)		
	12	12	3.28(−07)	3.2(−07)	7.54(−03)	5.1(−03)
	12	14	7.65(−06)	7.1(−06)	2.85(−04)	1.6(−04)
	6	4	5.96(−03)	3.7(−03)	0.0151	0.010
	6	6	3.70(−04)	3.3(−04)	0.176	0.13
	8	4	2.09(−03)	1.3(−03)		
	8	6	7.37(−04)	5.9(−04)	0.171	0.12
	10	6	2.65(−04)	2.1(−04)		
$^4G - ^3^2F$	6	6	0.0134	4.5(−03)	0.140	0.21
	6	8	9.04(−05)	2.7(−05)	0.0155	0.015
	8	6	0.0229	8.1(−03)	0.463	0.47
	8	8	8.43(−04)	2.3(−04)	0.0825	0.080
	10	6	0.0120	4.1(−03)		
	10	8	1.57(−03)	4.6(−04)	0.569	0.50
	12	8	5.21(−04)	1.4(−04)		
	6	4	0.195	0.18	0.157	0.14
	8	4	0.0788	0.071		
	6	6	0.0621	0.064	0.287	0.19
$^4G - ^4F$	8	6	0.109	0.11	0.0209	9.4(−04)
	10	6	0.0594	0.061		
	6	8	6.59(−03)	4.1(−03)	0.0156	0.014
	8	8	0.0713	0.067	0.156	0.13
	10	8	0.155	0.15	0.0514	0.039
	12	8	0.0436	0.040		
	6	10	8.88(−05)	8.7(−05)		
	8	10	3.92(−03)	3.8(−03)	0.0125	0.0023
	10	10	0.0474	0.045	0.0733	0.073
	12	10	0.223	0.21	0.160	0.11
$^4G - ^2H$	6	10	5.32(−08)	1.9(−06)		
	8	10	4.40(−05)	3.4(−05)	0.179	0.13
	8	12	8.41(−07)	v.s.		
	10	10	5.52(−04)	4.8(−04)	0.201	0.042
	10	12	1.07(−07)	7.8(−05)	0.228	0.61
	12	10	2.12(−03)	1.3(−03)	0.0150	0.56
	12	12	6.30(−07)	v.s.	0.554	0.47
	2	4	2.50(−05)	7.0(−06)	0.0718	0.065
	2	6	2.24(−07)	1.1(−07)		
	4	4	4.89(−05)	2.0(−05)	0.280	0.25
$^4P - ^5^2D$	4	6	8.94(−06)	5.9(−06)	0.112	0.10
	6	4	1.82(−05)	7.3(−06)	0.0763	0.069
	6	6	8.50(−06)	2.8(−06)	0.594	0.54
	2	6	1.02(−05)	2.4(−05)		
	4	6	1.32(−04)	1.5(−05)	0.0157	0.013
	4	8	2.42(−05)	2.0(−05)		
$^4P - ^3^2F$	6	6	2.79(−04)	7.1(−05)	0.101	0.087
	6	8	7.97(−06)	2.5(−07)	5.87(−04)	5(−04)
	2	6	1.28(−03)	5.4(−04)		
	4	6	7.19(−04)	3.0(−04)	0.0128	0.021
	4	8	6.91(−05)	2.3(−05)		
	6	6	1.91(−03)	7.1(−04)	4.85(−03)	0.022
$^4D - ^3^2F$	6	8	8.34(−05)	2.8(−05)	0.0405	0.034
	8	6	4.62(−04)	1.9(−04)	8.72(−05)	7.2(−04)
	8	8	9.54(−05)	3.3(−05)	0.0994	0.10

Table 5 – continued

Multiplet	g_i	g_k	E2		M1	
			Present	Garstang	Present	Garstang
$^4D - ^4F$	2	4	7.62(−03)	8.3(−03)	0.107	0.10
	2	6	6.67(−03)	7.7(−03)		
	4	4	0.0151	0.016	0.177	0.16
	4	6	3.35(−03)	4.1(−03)	0.0327	0.023
	4	8	8.26(−03)	8.5(−03)		
	6	4	4.34(−03)	4.5(−03)	0.0432	0.039
	6	6	0.0110	0.012	0.216	0.18
	6	8	8.82(−03)	9.2(−03)	8.32(−03)	9.4(−03)
	6	10	5.79(−03)	5.7(−03)		
	8	4	1.92(−04)	1.9(−04)		
$^4F - ^5^2F$	8	6	1.95(−03)	2.1(−03)	0.0330	0.028
	8	8	0.0102	0.011	0.120	0.10
	8	10	0.0221	0.023	0.151	0.14
	4	6	5.08(−08)	6.8(−08)	0.111	0.098
	6	6	1.34(−04)	3.1(−05)	0.0200	0.016
	8	6	3.54(−06)	7.2(−07)	0.0399	0.027
	10	6	2.18(−06)	1.1(−07)		
	4	8	1.52(−08)	3.3(−09)		
	6	8	2.02(−05)	5.4(−06)	0.0242	0.026
	8	8	2.78(−05)	7.0(−06)	0.0333	0.013
$^5^2G - ^3^2G$	10	8	7.12(−08)	4.7(−08)	0.129	0.11
	8	8	0.460	0.40	2.56(−04)	v.s.
	10	8	0.0335	0.028	0.277	0.0053
	8	10	0.0371	0.033	0.258	0.029
	10	10	0.365	0.29	1.71(−04)	0.017
	6	4	7.29(−03)	7.1(−03)	0.102	0.10
	8	4	1.38(−03)	1.3(−03)		
	6	6	1.11(−03)	1.3(−03)	0.148	0.18
	8	6	6.87(−03)	7.2(−03)	0.103	0.10
	6	8	0.0570	0.055	0.107	0.091
$^5^2F - ^3^2G$	6	10	3.78(−03)	2.9(−03)		
	8	8	8.66(−03)	7.1(−03)	0.284	0.22
	8	10	0.0583	0.058	0.109	0.10

Note: v.s. means very small in Garstang (1958) compilation.

their observed feature at 4903.32 Å. This presumably is the $^2F_{5/2} \rightarrow ^2P_{3/2}$ transition, which would be blended with any putative [Fe iv] 4903.07 Å.

We predict $I(4903)/I(4900) = 1.10$, with Garstang transition probabilities predicting nearly the same ratio (1.04). Liu et al. have observed fluxes $F(4899.21) = 0.012$ and $F(4903.32) = 0.039$ scaled to $F(H\beta) = 100$. Hence from the observed flux ratio (3.2), one would conclude that the [Fe vi] 4903.3-Å line is the major contributor to the observed blend (subject to observational uncertainties). There are indeed other [Fe vi] lines that they list as observed in NGC 6884. Besides the RR Tel data, to the best of our knowledge, this is the only other instance of astronomically observed [Fe iv] multiple lines that originate from the same level and thus in principle allow a direct test of the calculated A_{ki} ratio. However, in this case, the test is not a clean one because of the likely blending of the [Fe iv] line with an [Fe vi] line.

It is beyond the scope of this paper to extract additional information from the current rather sparse number of [Fe iv] lines observed in a given nebula. To do this involves a detailed population statistical equilibrium set of equations that uses effective collision strengths as well as transition probabilities to predict [Fe iv] line intensities as a function of N_e and T_e . By providing this improved set of A -values, the ingredients to do such a calculation are in place. A machine-readable file is available, by contacting either author by e-mail, that

provides the sum of the M1 + E2 transition probabilities for the entries in the Appendix.

ACKNOWLEDGMENTS

This work was supported by the Chemical Sciences, Geosciences and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy. Support for RHR was from the NASA Long-Term Space Astrophysics (LTS) program. We thank Dafna Bitton for assistance with preparing the tables, Mónica Rodríguez for helpful comments and Xiao-wei Liu for an advance copy of Liu et al. (2004).

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APPENDIX

Shown in Table A1 are selected multiplets with linestrengths, S, oscillator strengths, f_{ik} , and transition probabilities, A_{ki} , based on observed wavelengths (vacuum).

Table A1. Selected multiplets with line-strengths, S, oscillator strengths, f_{ik} , and transition probabilities, A_{ki} , based on observed wavelengths.

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})
$3d^5 \ ^5S - 3d^5 \ ^4G$								
6S	4	6	6	E2	3095.86	3.504e-08	3.292e-17	2.30e-08
		6	8	E2	3095.43	6.734e-08	6.351e-17	3.32e-08
		6	10	E2	3096.67	4.702e-09	4.437e-18	1.85e-09
		6	6	M1	3095.86	1.422e-07	3.092e-14	2.16e-05
		6	8	M1	3095.43	5.028e-10	1.095e-16	5.72e-08
$3d^5 \ ^5S - 3d^5 \ ^3P$								
6S	4	6	2	E2	2824.33	4.705e-08	5.840e-17	1.47e-07
		6	4	E2	2830.19	7.854e-06	9.719e-15	1.21e-05
		6	6	E2	2836.57	3.951e-05	4.834e-14	4.02e-05
		6	4	M1	2830.19	3.421e-03	8.152e-10	1.02e+00
		6	6	M1	2836.57	7.938e-03	1.885e-09	1.56e+00
$3d^5 \ ^5S - 3d^5 \ ^4D$								
6S	4	6	2	E2	2570.91	4.344e-05	7.165e-14	2.17e-04
		6	4	E2	2568.17	2.923e-04	4.843e-13	7.33e-04
		6	6	E2	2568.38	7.354e-04	1.218e-12	1.23e-03
		6	8	E2	2578.69	1.030e-03	1.682e-12	1.27e-03
		6	4	M1	2568.17	8.355e-05	2.195e-11	3.33e-02
		6	6	M1	2568.38	2.502e-04	6.572e-11	6.64e-02
		6	8	M1	2578.69	3.901e-06	1.020e-12	7.67e-04
$3d^5 \ ^5S - 3d^5 \ ^2D$								
6S	2	6	4	E2	1997.95	3.307e-09	1.168e-17	2.91e-08
		6	6	E2	2018.51	9.271e-10	3.163e-18	5.16e-09
		6	4	M1	1997.95	2.451e-07	8.289e-14	2.07e-04
		6	6	M1	2018.51	3.146e-06	1.051e-12	1.72e-03
$3d^5 \ ^5S - 3d^5 \ ^3F$								
6S	2	6	6	E2	1916.93	8.359e-08	3.333e-16	6.03e-07
		6	8	E2	1945.74	5.419e-07	2.059e-15	2.72e-06
		6	6	M1	1916.93	3.144e-07	1.107e-13	2.01e-04
		6	8	M1	1945.74	5.005e-10	1.734e-16	2.29e-07
$3d^5 \ ^5S - 3d^5 \ ^4F$								
6S	4	6	4	E2	1892.61	2.238e-10	9.268e-19	2.58e-09
		6	6	E2	1892.58	8.331e-09	3.450e-17	6.40e-08
		6	8	E2	1897.70	1.427e-08	5.850e-17	8.12e-08
		6	10	E2	1900.39	4.203e-07	1.713e-15	1.90e-06
		6	4	M1	1892.61	9.368e-09	3.340e-15	9.32e-06
		6	6	M1	1892.58	1.848e-07	6.587e-14	1.23e-04
		6	8	M1	1897.70	8.169e-10	2.902e-16	4.03e-07
$3d^5 \ ^5S - 3d^5 \ ^2H$								
6S	2	6	10	E2	1783.86	5.089e-09	2.513e-17	3.15e-08
$3d^5 \ ^5S - 3d^5 \ ^5G$								
6S	2	6	8	E2	1741.92	6.241e-09	3.305e-17	5.45e-08
		6	10	E2	1732.47	1.395e-08	7.517e-17	1.00e-07
$3d^5 \ ^5S - 3d^5 \ ^2F$								
6S	2	6	6	E2	1635.15	1.064e-09	6.800e-18	1.70e-08
		6	8	E2	1632.54	1.627e-08	1.047e-16	1.96e-07
		6	6	M1	1635.15	6.177e-12	2.545e-18	6.35e-09
		6	8	M1	1632.54	5.950e-12	2.456e-18	4.61e-09
$3d^5 \ ^5S - 3d^5 \ ^2S$								
6S	2	6	2	E2	1498.80	1.894e-09	1.574e-17	1.40e-07
$3d^5 \ ^5S - 3d^5 \ ^3D$								
6S	2	6	4	E2	1349.59	1.585e-08	1.804e-16	9.91e-07
		6	6	E2	1348.93	5.887e-08	6.715e-16	2.46e-06
		6	4	M1	1349.59	9.232e-12	4.610e-18	2.53e-08
		6	6	M1	1348.93	4.099e-12	2.048e-18	7.51e-09
$3d^5 \ ^5S - 3d^5 \ ^3G$								
6S	2	6	8	E2	1206.31	2.805e-08	4.479e-16	1.54e-06
		6	10	E2	1206.35	3.461e-07	5.517e-15	1.52e-05
$3d^5 \ ^5S - 3d^5 \ ^3P$								
6S	2	6	2	E2	998.74	1.276e-07	3.583e-15	7.19e-05
		6	4	E2	998.82	4.447e-07	1.249e-14	1.25e-04
		6	4	M1	998.82	1.130e-10	7.627e-17	7.65e-07
$3d^5 \ ^5S - 3d^5 \ ^1D$								
6S	2	6	4	E2	923.72	3.076e-10	1.092e-17	1.28e-07
		6	6	E2	923.85	7.370e-11	2.614e-18	2.04e-08
		6	4	M1	923.72	8.875e-10	6.476e-16	7.59e-06
		6	6	M1	923.85	1.033e-08	7.537e-15	5.89e-05
$3d^5 \ ^5G - 3d^5 \ ^4G$								
4G	4	6	8	M1	2.22e+07	1.282e+01	3.459e-09	3.94e-09
		10	8	M1	7.75e+06	1.707e+01	8.911e-10	1.24e-07
		12	10	M1	2.11e+06	1.307e+01	2.710e-09	3.73e-06
$3d^5 \ ^5G - 3d^5 \ ^3P$								
4G	4	6	2	E2	32201.97	2.488e-05	2.154e-17	4.02e-10
		6	4	E2	32980.44	1.816e-04	1.518e-16	1.30e-09
		6	6	E2	33868.45	4.448e-04	3.259e-16	1.86e-09
		8	4	E2	33029.46	2.250e-04	1.356e-16	1.60e-09
		8	6	E2	33920.15	8.853e-04	4.671e-16	3.68e-09
		10	6	E2	33772.37	1.764e-04	7.396e-17	7.50e-10
		6	4	M1	32980.44	9.086e-05	1.900e-12	1.71e-05
		6	6	M1	33868.45	1.137e-03	2.275e-11	1.32e-04
		8	6	M1	33920.15	2.060e-04	3.050e-12	2.37e-05
$3d^5 \ ^5G - 3d^5 \ ^3D$								
4G	4	6	2	E2	15161.85	1.727e-04	1.426e-15	1.21e-07
		6	4	E2	15067.05	3.218e-03	2.724e-14	1.16e-06
		6	6	E2	15074.09	4.998e-03	4.221e-14	1.20e-06
		6	8	E2	15436.39	4.648e-04	3.603e-15	7.42e-08

Table A1 – continued

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})
$3d^5 5^4G - 3d^5 5^2I$	8 4 E2	15077.27	2.558e-03	1.595e-14	9.19e-07			
	8 6 E2	15084.32	8.329e-03	5.183e-14	1.99e-06			
	8 8 E2	15447.12	6.987e-03	3.987e-14	1.11e-06			
	10 6 E2	15055.03	4.511e-03	2.239e-14	1.09e-06			
	10 8 E2	15416.40	1.726e-02	7.855e-14	2.77e-06			
	12 8 E2	15304.79	1.555e-03	6.068e-15	2.59e-07			
	6 4 M1	15067.05	2.214e-04	1.002e-11	4.37e-04			
	6 6 M1	15074.09	7.694e-04	3.479e-11	1.01e-03			
	6 8 M1	15436.39	1.447e-04	6.357e-12	1.33e-04			
	8 6 M1	15084.32	1.283e-08	4.326e-16	1.68e-08			
	8 8 M1	15447.12	1.457e-03	4.772e-11	1.33e-03			
	10 8 M1	15416.40	1.191e-03	3.116e-11	1.10e-03			
$3d^5 5^4G - 3d^5 5^2D$	8 12 E2	6769.15	1.741e-04	1.180e-14	1.14e-06			
	10 12 E2	6763.25	3.961e-04	2.145e-14	2.61e-06			
	10 14 E2	6757.81	1.553e-04	8.550e-15	8.81e-07			
	12 12 E2	6741.68	4.900e-05	2.239e-15	3.28e-07			
	12 14 E2	6736.27	1.327e-03	6.166e-14	7.65e-06			
	10 12 M1	6763.25	3.191e-04	1.907e-11	2.32e-03			
	12 12 M1	6741.68	1.028e-03	5.141e-11	7.54e-03			
	12 14 M1	6736.27	4.518e-05	2.272e-12	2.85e-04			
$3d^5 5^4G - 3d^5 5^2F$	6 4 E2	5633.74	1.207e-01	1.940e-11	5.96e-03			
	6 6 E2	5800.36	1.303e-02	1.896e-12	3.70e-04			
	8 4 E2	5635.17	4.235e-02	5.068e-12	2.09e-03			
	8 6 E2	5801.88	2.595e-02	2.812e-12	7.37e-04			
	10 6 E2	5797.54	9.300e-03	8.053e-13	2.65e-04			
	6 4 M1	5633.74	3.991e-04	4.817e-11	1.51e-02			
	6 6 M1	5800.36	7.626e-03	8.904e-10	1.76e-01			
	8 6 M1	5801.88	7.431e-03	6.492e-10	1.71e-01			
$3d^5 5^4G - 3d^5 3^2F$	6 6 E2	5033.85	2.328e-01	5.190e-11	1.34e-02			
	6 8 E2	5237.52	2.546e-03	4.992e-13	9.04e-05			
	8 6 E2	5034.99	3.963e-01	6.586e-11	2.29e-02			
	8 8 E2	5238.76	2.377e-02	3.474e-12	8.43e-04			
	10 6 E2	5031.73	2.080e-01	2.762e-11	1.20e-02			
	10 8 E2	5235.22	4.397e-02	5.135e-12	1.57e-03			
	12 8 E2	5222.29	1.444e-02	1.419e-12	5.21e-04			
	6 6 M1	5033.85	3.974e-03	5.349e-10	1.40e-01			
	6 8 M1	5237.52	6.622e-04	8.539e-11	1.55e-02			
	8 6 M1	5034.99	1.315e-02	1.325e-09	4.63e-01			
	8 8 M1	5238.76	3.518e-03	3.396e-10	8.25e-02			
	10 8 M1	5235.22	2.421e-02	1.869e-09	5.69e-01			
$3d^5 5^4G - 3d^5 3^4F$	6 4 E2	4869.52	1.909e+00	4.693e-10	1.95e-01			
	6 6 E2	4869.31	9.110e-01	2.239e-10	6.21e-02			
	6 8 E2	4903.35	1.335e-01	3.195e-11	6.59e-03			
	6 10 E2	4921.38	2.290e-03	5.400e-13	8.88e-05			
	8 4 E2	4870.59	7.710e-01	1.413e-10	7.88e-02			
	8 6 E2	4870.37	1.597e+00	2.928e-10	1.09e-01			
	8 8 E2	4904.44	1.445e+00	2.580e-10	7.13e-02			
	8 10 E2	4922.47	1.011e-01	1.778e-11	3.92e-03			
	10 6 E2	4867.32	8.689e-01	1.273e-10	5.94e-02			
	10 8 E2	4901.34	3.128e+00	4.462e-10	1.55e-01			
	10 10 E2	4919.35	1.219e+00	1.713e-10	4.74e-02			
	12 8 E2	4890.00	8.714e-01	1.045e-10	4.36e-02			
	12 10 E2	4907.93	5.680e+00	6.714e-10	2.23e-01			
	6 4 M1	4869.52	2.683e-03	3.731e-10	1.57e-01			
	6 6 M1	4869.31	7.369e-03	1.025e-09	2.87e-01			
	6 8 M1	4903.35	5.472e-04	7.543e-11	1.56e-02			
	8 6 M1	4870.37	5.364e-04	5.584e-11	2.09e-02			
	8 8 M1	4904.44	5.454e-03	5.627e-10	1.56e-01			
	8 10 M1	4922.47	5.534e-04	5.682e-11	1.25e-02			
	10 8 M1	4901.34	1.797e-03	1.482e-10	5.14e-02			

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})
$3d^5 5^4G - 3d^5 3^2H$	10 10 M1	4919.35	3.237e-03	2.658e-10	7.33e-02			
	12 10 M1	4907.93	7.010e-03	4.811e-10	1.60e-01			
	4 6 E2	4209.27	6.272e-07	2.376e-16	5.32e-08			
	8 10 E2	4210.07	5.194e-04	1.468e-13	4.40e-05			
	8 12 E2	4155.74	1.116e-05	3.288e-15	8.41e-07			
	10 10 E2	4207.78	6.500e-03	1.469e-12	5.52e-04			
	10 12 E2	4153.51	1.415e-06	3.332e-16	1.07e-07			
	12 10 E2	4199.42	2.470e-02	4.688e-12	2.12e-03			
	12 12 E2	4145.37	8.265e-06	1.634e-15	6.30e-07			
	8 10 M1	4210.07	4.960e-03	5.965e-10	1.79e-01			
	10 10 M1	4207.78	5.555e-03	5.343e-10	2.01e-01			
	10 12 M1	4153.51	7.259e-03	7.078e-10	2.28e-01			
	12 10 M1	4199.42	4.125e-04	3.315e-11	1.50e-02			
	12 12 M1	4145.37	1.755e-02	1.430e-09	5.54e-01			
$3d^5 5^4G - 3d^5 5^2G$	6 8 E2	3982.98	6.709e-04	2.987e-13	9.37e-05			
	6 10 E2	3933.91	5.081e-05	2.353e-14	6.04e-06			
	8 8 E2	3983.70	5.460e-03	1.814e-12	7.62e-04			
	8 10 E2	3934.61	1.366e-03	4.723e-13	1.62e-04			
	10 8 E2	3981.65	7.985e-03	2.121e-12	1.12e-03			
	10 10 E2	3932.61	1.342e-02	3.709e-12	1.60e-03			
	12 8 E2	3974.17	2.570e-03	5.732e-13	3.63e-04			
	12 10 E2	3925.31	5.148e-02	1.194e-11	6.19e-03			
	6 8 M1	3982.98	1.011e-05	1.714e-12	5.40e-04			
	8 8 M1	3983.70	2.202e-07	2.795e-14	1.17e-05			
	8 10 M1	3934.61	8.140e-04	1.047e-10	3.61e-02			
	10 8 M1	3981.65	4.486e-06	4.554e-13	2.40e-04			
	10 10 M1	3932.61	5.596e-04	5.756e-11	2.48e-02			
	12 10 M1	3925.31	3.301e-07	2.836e-14	1.47e-05			
$3d^5 5^4G - 3d^5 3^2F$	6 6 E2	3465.57	1.374e-05	9.250e-15	5.13e-06			
	6 8 E2	3453.85	4.685e-06	3.197e-15	1.33e-06			
	8 6 E2	3466.11	1.323e-02	6.651e-12	4.93e-03			
	8 8 E2	3454.39	1.303e-03	6.641e-13	3.71e-04			
	10 6 E2	3464.56	1.753e-03	7.049e-13	6.56e-04			
	10 8 E2	3452.85	2.049e-02	8.349e-12	5.84e-03			
	12 8 E2	3447.22	1.368e-04	4.674e-14	3.93e-05			
	6 6 M1	3465.57	1.804e-06	3.510e-13	1.95e-04			
	6 8 M1	3453.85	5.462e-06	1.068e-12	4.47e-04			
	8 6 M1	3466.11	3.847e-05	5.605e-12	4.15e-03			
	8 8 M1	3454.39	6.812e-07	9.970e-14	5.57e-05			
	10 8 M1	3452.85	7.614e-05	8.914e-12	6.24e-03			
$3d^5 5^4G - 3d^5 3^2S$	6 6 E2	2905.38	2.134e-07	2.443e-16	5.77e-07			
$3d^5 5^4G - 3d^5 3^2D$	6 4 E2	2392.61	1.645e-05	3.371e-14	5.87e-05			
	6 6 E2	2390.52	2.850e-06	5.862e-15	6.82e-06			
	8 4 E2	2392.87	6.071e-06	9.304e-15	2.17e-05			
	8 6 E2	2390.78	2.433e-06	3.743e-15	5.82e-06			
	10 6 E2	2390.04	1.423e-06	1.750e-15	3.41e-06			
	6 4 M1	2392.61	3.511e-08	9.900e-15	1.73e-05			
	6 6 M1	2390.52	5.728e-08	1.617e-14	1.89e-05			
	8 6 M1	2390.78	6.563e-08	1.388e-14	2.16e-05			
$3d^5 5^4G - 3d^5 3^2G$	6 8 E2	1976.44	1.366e-05	4.976e-14	6.34e-05			
	6 10 E2	1976.53	8.101e-06	2.943e-14	3.01e-05			
	8 8 E2	1976.61	2.830e-09	7.714e-18	1.31e-08			
	8 10 E2	1976.71	3.111e-06	8.457e-15	1.15e-05			
	10 8 E2	1976.11	5.103e-06	1.112e-14	2.37e-05			
	10 10 E2	1976.20	6.453e-06	1.403e-14	2.40e-05			
	12 8 E2	1974.26	2.991e-05	5.454e-14	1.40e-04			
	12 10 E2	1974.36	3.757e-08	6.830e-17	1.40e-07			
	6 8 M1	1976.44	3.619e-04	1.236e-10	1.58e-01			

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})	
$3d^5 \ 5^4G - 3d^5 \ 3^2P$	8	8	M1	1976.61	3.911e-05	1.001e-11	1.71e-02		
	8	10	M1	1976.71	1.834e-04	4.690e-11	6.40e-02		
	10	8	M1	1976.11	9.050e-05	1.853e-11	3.95e-02		
	10	10	M1	1976.20	4.535e-05	9.278e-12	1.59e-02		
	12	10	M1	1974.36	4.624e-04	7.893e-11	1.62e-01		
$4G \ 2P$	6	2	E2	1474.39	1.536e-06	1.343e-14	1.23e-04		
	6	4	E2	1474.56	5.160e-05	4.512e-13	2.07e-03		
	8	4	E2	1474.66	1.134e-06	7.422e-15	4.55e-05		
	6	4	M1	1474.56	3.584e-10	1.639e-16	7.54e-07		
$3d^5 \ 5^4G - 3d^5 \ 1^2D$	$4G \ 2D$	6	4	E2	1316.53	1.292e-03	1.587e-11	9.15e-02	
	6	6	E2	1316.81	3.319e-04	4.071e-12	1.57e-02		
	8	4	E2	1316.61	2.473e-04	2.275e-12	1.75e-02		
	8	6	E2	1316.89	7.276e-04	6.682e-12	3.43e-02		
	10	6	E2	1316.67	6.729e-05	4.943e-13	3.17e-03		
	6	4	M1	1316.53	3.427e-08	1.755e-14	1.01e-04		
	6	6	M1	1316.81	1.222e-09	6.255e-16	2.41e-06		
	8	6	M1	1316.89	1.184e-07	4.544e-14	2.33e-04		
$3d^5 \ 3^4P - 3d^5 \ 3^4P$	$4P \ 4P$	6	2	E2	6.54e+05	3.181e-02	4.338e-18	1.48e-13	
	4	2	M1	1.36e+06	3.352e+00	1.246e-09	1.78e-05		
	6	4	M1	1.26e+06	3.739e+00	3.346e-09	1.27e-05		
$3d^5 \ 3^4P - 3d^5 \ 5^4D$	$4P \ 4D$	2	4	E2	28315.78	1.960e-01	7.510e-13	3.01e-06	
	2	6	E2	28340.65	5.101e-01	1.947e-12	5.21e-06		
	4	2	E2	28063.09	3.622e-01	6.835e-13	1.17e-05		
	4	4	E2	27740.02	3.238e-01	6.398e-13	5.52e-06		
	4	6	E2	27763.90	2.170e-02	4.272e-14	2.46e-07		
	4	8	E2	29018.31	7.306e-01	1.223e-12	4.97e-06		
	6	2	E2	27450.66	4.554e-02	6.396e-14	1.64e-06		
	6	4	E2	27141.46	2.945e-01	4.323e-13	5.60e-06		
	6	6	E2	27164.32	7.263e-01	1.062e-12	9.17e-06		
	6	8	E2	28363.97	1.103e+00	1.380e-12	8.41e-06		
	2	2	M1	28652.47	1.233e-01	8.772e-09	7.07e-02		
	2	4	M1	28315.78	7.421e-03	5.362e-10	2.20e-03		
	4	2	M1	28063.09	7.320e-02	2.632e-09	4.47e-02		
	4	4	M1	27740.02	1.497e-01	5.464e-09	4.73e-02		
	4	6	M1	27763.90	2.128e-02	7.758e-10	4.47e-03		
	6	4	M1	27141.46	6.243e-02	1.575e-09	2.11e-02		
	6	6	M1	27164.32	1.170e-01	2.948e-09	2.62e-02		
	6	8	M1	28363.97	3.088e-01	7.385e-09	4.56e-02		
$3d^5 \ 3^4P - 3d^5 \ 5^2D$	$4P \ 2D$	2	4	E2	6828.36	1.325e-03	3.582e-13	2.50e-05	
	2	6	E2	7074.69	2.126e-05	5.093e-15	2.24e-07		
	4	4	E2	6794.36	2.529e-03	3.444e-13	4.89e-05		
	4	6	E2	7038.19	8.273e-04	9.988e-14	8.94e-06		
	6	4	E2	6757.85	9.179e-04	8.559e-14	1.82e-05		
	6	6	E2	6999.03	7.648e-04	6.329e-14	8.50e-06		
	2	4	M1	6828.36	3.389e-03	1.012e-09	7.18e-02		
	4	4	M1	6794.36	1.304e-02	1.951e-09	2.80e-01		
	4	6	M1	7038.19	8.711e-03	1.252e-09	1.12e-01		
	6	4	M1	6757.85	3.493e-03	3.516e-10	7.63e-02		
	6	6	M1	6999.03	4.527e-02	4.380e-09	5.94e-01		
$3d^5 \ 3^4P - 3d^5 \ 3^2F$	$4P \ 2F$	2	6	E2	5966.55	4.130e-04	1.654e-13	1.02e-05	
	4	6	E2	5940.57	5.216e-03	1.051e-12	1.32e-04		
	4	8	E2	6226.30	1.616e-03	2.796e-13	2.42e-05		
	6	6	E2	5912.65	1.081e-02	1.487e-12	2.79e-04		
	6	8	E2	6195.63	5.198e-04	6.145e-14	7.97e-06		
	4	6	M1	5940.57	7.325e-04	1.249e-10	1.57e-02		
	6	6	M1	5912.65	4.658e-03	5.338e-10	1.01e-01		
	6	8	M1	6195.63	4.142e-05	4.512e-12	5.87e-04		
$3d^5 \ 3^4P - 3d^5 \ 3^4F$	$4P \ 4F$	2	4	E2	5737.07	2.243e-02	1.008e-11	1.01e-03	

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})
		2	6	E2	5736.77	1.690e-04	7.597e-14	5.08e-06
		4	4	E2	5713.05	4.611e-02	1.043e-11	2.12e-03
		4	6	E2	5712.75	2.987e-02	6.755e-12	9.16e-04
		4	8	E2	5759.67	8.659e-03	1.898e-12	1.91e-04
		6	4	E2	5687.21	1.330e-02	2.052e-12	6.26e-04
		6	6	E2	5686.92	4.583e-02	7.069e-12	1.44e-03
		6	8	E2	5733.42	6.778e-02	1.014e-11	1.53e-03
		6	10	E2	5758.08	1.329e-02	1.954e-12	2.35e-04
		2	4	M1	5737.07	2.092e-05	7.398e-12	7.47e-04
		4	4	M1	5713.05	4.284e-05	7.592e-12	1.55e-03
		4	6	M1	5712.75	2.700e-04	4.785e-11	6.51e-03
		6	4	M1	5687.21	1.035e-05	1.232e-12	3.79e-04
		6	6	M1	5686.92	8.529e-04	1.015e-10	2.08e-02
		6	8	M1	5733.42	7.086e-05	8.349e-12	1.27e-03
$3d^5 \ 3^4P - 3d^5 \ 3^2H$	$4P \ 2H$	6	10	E2	4806.65	2.938e-05	7.467e-15	1.28e-06
$3d^5 \ 3^4P - 3d^5 \ 5^2G$	$4P \ 2G$	4	8	E2	4530.07	8.831e-06	3.973e-15	6.48e-07
		6	8	E2	4513.82	4.035e-04	1.232e-13	3.01e-05
		6	10	E2	4450.89	4.653e-05	1.486e-14	2.98e-06
		6	8	M1	4513.82	1.102e-06	1.647e-13	4.04e-05
$3d^5 \ 3^4P - 3d^5 \ 5^2F$	$4P \ 2F$	2	6	E2	3883.51	4.548e-06	6.504e-15	9.61e-07
		4	6	E2	3872.49	1.433e-04	1.029e-13	3.07e-05
		4	8	E2	3857.86	8.407e-05	6.128e-14	1.38e-05
		6	6	E2	3860.60	5.157e-06	2.507e-15	1.12e-06
		6	8	E2	3846.07	5.151e-04	2.542e-13	8.57e-05
		4	6	M1	3872.49	1.288e-06	3.354e-13	9.97e-05
		6	6	M1	3860.60	3.018e-08	5.267e-15	2.36e-06
		6	8	M1	3846.07	5.622e-09	9.862e-16	3.33e-07
$3d^5 \ 3^4P - 3d^5 \ 5^2S$	$4P \ 2S$	4	2	E2	3186.05	1.128e-05	1.461e-14	1.92e-05
		6	2	E2	3178.00	5.297e-05	4.629e-14	9.15e-05
		2	2	M1	3193.51	3.873e-04	2.453e-10	1.60e-01
		4	2	M1	3186.05	1.911e-03	6.059e-10	7.97e-01
$3d^5 \ 3^4P - 3d^5 \ 3^2D$	$4P \ 2D$	2	4	E2	2584.65	3.494e-04	1.700e-12	8.48e-04
		2	6	E2	2582.21	2.566e-04	1.253e-12	4.17e-04
		4	4	E2	2579.76	1.628e-04	3.971e-13	3.99e-04
		4	6	E2	2577.33	3.835e-04	9.392e-13	6.30e-04
		6	4	E2	2574.48	8.638e-04	1.419e-12	2.14e-03
		6	6	E2	2572.06	3.208e-03	5.292e-12	5.32e-03
		2	4	M1	2584.65	1.256e-05	9.829e-12	4.91e-03
		4	4	M1	2579.76	7.295e-06	2.857e-12	2.87e-03
		4	6	M1	2577.33	4.788e-05	1.877e-11	1.26e-02
		6	4	M1	2574.48	2.029e-05	5.315e-12	8.02e-03
		6	6	M1	2572.06	1.339e-05	3.513e-12	3.54e-03
$3d^5 \ 3^4P - 3d^5 \ 3^2G$	$4P \ 2G$	4	8	E2	2102.43	3.216e-04	1.454e-12	1.10e-03
		6	8	E2	2098.92	2.272e-04	6.907e-13	7.81e-04
		6	10	E2	2099.03	2.566e-03	7.775e-12	7.05e-03
		6	8	M1	2098.92	8.749e-09	2.813e-15	3.19e-06
$3d^5 \ 3^4P - 3d^5 \ 3^2P$	$4P \ 2P$	2	4	E2	1545.32	5.418e-06	1.233e-13	1.72e-04
		4	2	E2	1543.38	1.644e-04	1.874e-12	1.05e-02
		4	4	E2	1543.57	4.073e-04	4.643e-12	1.30e-02
		6	2	E2	1541.49	1.059e-03	8.096e-12	6.81e-02
		6	4	E2	1541.68	3.813e-03	2.916e-11	1.23e-01
		2	2	M1	1545.13	6.100e-07	7.983e-13	2.23e-03
		2	4	M1	1545.32	1.948e-07	2.550e-13	3.56e-04
		4	2	M1	1543.38	2.643e-06	1.731e-12	9.70e-03
		4	4	M1	1543.57	1.346e-06	8.814e-13	2.47e-03
		6	4	M1	1541.68	5.430e-06	2.375e-12	9.99e-03
$3d^5 \ 3^4P - 3d^5 \ 1^2D$	$4P \ 2D$	2	4	E2	1372.65	6.360e-07	2.066e-1	

Table A1 – continued

Multiplet	g _i	g _k	Type	λ (Å)	S	f _{ik}	A _{ki} (s ⁻¹)
	2	6	E2	1372.96	1.214e-07	3.935e-15	4.64e-06
	4	4	E2	1371.27	4.226e-07	6.872e-15	2.44e-05
	4	6	E2	1371.58	1.664e-07	2.702e-15	6.40e-06
	6	4	E2	1369.78	2.826e-06	3.081e-14	1.64e-04
	6	6	E2	1370.08	3.329e-05	3.622e-13	1.29e-03
	2	4	M1	1372.65	1.443e-05	2.126e-11	3.76e-02
	4	4	M1	1371.27	5.393e-05	3.975e-11	1.41e-01
	4	6	M1	1371.58	4.138e-05	3.048e-11	7.21e-02
	6	4	M1	1369.78	1.158e-05	5.702e-12	3.04e-02
	6	6	M1	1370.08	2.209e-04	1.087e-10	3.86e-01
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i>							
<i>4D</i> <i>4D</i>	2	4	M1	2.41e+06	5.887e+00	6.512e-09	2.84e-06
	6	4	M1	3.23e+07	8.155e+00	2.564e-10	1.64e-09
	8	6	M1	6.42e+05	6.548e+00	6.280e-09	1.11e-04
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ² <i>I</i>							
<i>4D</i> <i>2I</i>	8	12	E2	12049.35	5.085e-07	6.108e-18	1.87e-10
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ² <i>D</i>							
<i>4D</i> <i>2D</i>	2	4	E2	8964.83	3.297e-02	3.938e-12	1.59e-04
	2	6	E2	9394.26	1.058e-02	1.078e-12	2.70e-05
	4	4	E2	8998.31	5.099e-02	3.001e-12	2.42e-04
	4	6	E2	9431.03	7.917e-03	3.970e-13	1.98e-05
	6	4	E2	8995.80	1.731e-02	6.799e-13	8.23e-05
	6	6	E2	9428.27	5.383e-03	1.802e-13	1.35e-05
	8	4	E2	8871.54	2.011e-03	6.232e-14	1.02e-05
	8	6	E2	9291.87	1.010e-02	2.675e-13	2.72e-05
	2	4	M1	8964.83	1.644e-04	3.740e-11	1.54e-03
	4	4	M1	8998.31	1.791e-06	2.027e-13	1.66e-05
	4	6	M1	9431.03	1.562e-04	1.675e-11	8.37e-04
	6	4	M1	8995.80	1.582e-05	1.194e-12	1.47e-04
	6	6	M1	9428.27	5.832e-06	4.172e-13	3.13e-05
	8	6	M1	9291.87	3.973e-04	2.170e-11	2.23e-03
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ² <i>F</i>							
<i>4D</i> <i>2F</i>	2	6	E2	7535.80	1.672e-01	3.312e-11	1.28e-03
	4	6	E2	7559.44	9.512e-02	9.307e-12	7.19e-04
	4	8	E2	8028.26	1.646e-02	1.325e-12	6.91e-05
	6	6	E2	7557.66	2.530e-01	1.652e-11	1.91e-03
	6	8	E2	8026.26	1.985e-02	1.066e-12	8.34e-05
	8	6	E2	7469.77	5.757e-02	2.942e-12	4.62e-04
	8	8	E2	7927.20	2.134e-02	8.994e-13	9.54e-05
	4	6	M1	7559.44	1.225e-03	1.642e-10	1.28e-02
	6	6	M1	7557.66	4.655e-04	4.162e-11	4.85e-03
	6	8	M1	8026.26	6.205e-03	5.197e-10	4.05e-02
	8	6	M1	7469.77	8.082e-06	5.496e-13	8.72e-05
	8	8	M1	7927.20	1.468e-02	9.362e-10	9.94e-02
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ⁴ <i>F</i>							
<i>4D</i> <i>4F</i>	2	4	E2	7173.40	5.172e-01	1.185e-10	7.62e-03
	2	6	E2	7172.93	6.790e-01	1.556e-10	6.67e-03
	4	4	E2	7194.81	1.041e+00	1.179e-10	1.51e-02
	4	6	E2	7194.35	3.455e-01	3.912e-11	3.35e-03
	4	8	E2	7268.92	1.197e+00	1.303e-10	8.26e-03
	6	4	E2	7193.21	2.986e-01	2.256e-11	4.34e-03
	6	6	E2	7192.74	1.135e+00	8.578e-11	1.10e-02
	6	8	E2	7267.28	1.277e+00	9.280e-11	8.82e-03
	6	10	E2	7306.95	1.076e+00	7.648e-11	5.79e-03
	8	4	E2	7113.54	1.251e-02	7.383e-13	1.92e-04
	8	6	E2	7113.08	1.902e-01	1.123e-11	1.95e-03
	8	8	E2	7185.97	1.400e+00	7.947e-11	1.02e-02
	8	10	E2	7224.75	3.888e+00	2.160e-10	2.21e-02
	2	4	M1	7173.40	5.862e-03	1.657e-09	1.07e-01
	4	4	M1	7194.81	9.791e-03	1.378e-09	1.77e-01
	4	6	M1	7194.35	2.707e-03	3.809e-10	3.27e-02
	6	4	M1	7193.21	2.384e-03	2.238e-10	4.32e-02
	6	6	M1	7192.74	1.791e-02	1.681e-09	2.16e-01
	6	8	M1	7267.28	9.467e-04	8.769e-11	8.32e-03

Table A1 – continued

Multiplet	g _i	g _k	Type	λ (Å)	S	f _{ik}	A _{ki} (s ⁻¹)
	8	6	M1	7113.08	2.646e-03	1.888e-10	3.30e-02
	8	8	M1	7185.97	1.321e-02	9.302e-10	1.20e-01
	8	10	M1	7224.75	2.107e-02	1.474e-09	1.51e-01
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ² <i>H</i>							
<i>4D</i> <i>2H</i>	6	10	E2	5840.03	3.995e-03	5.615e-13	6.59e-05
	8	10	E2	5787.41	2.514e-02	2.739e-12	4.34e-04
	8	12	E2	5685.24	2.997e-05	3.455e-15	4.71e-07
	8	10	M1	5787.41	1.192e-04	1.043e-11	1.66e-03
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ² <i>G</i>							
<i>4D</i> <i>2G</i>	4	8	E2	5414.24	1.935e-03	5.091e-13	5.82e-05
	6	8	E2	5413.34	8.156e-03	1.432e-12	2.46e-04
	6	10	E2	5323.08	7.545e-03	1.397e-12	1.98e-04
	8	8	E2	5368.09	6.760e-03	9.178e-13	2.12e-04
	8	10	E2	5279.33	5.873e-02	8.408e-12	1.60e-03
	6	8	M1	5413.34	5.909e-05	7.344e-12	1.26e-03
	8	8	M1	5368.09	7.017e-06	6.609e-13	1.53e-04
	8	10	M1	5279.33	3.231e-04	3.098e-11	5.92e-03
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ² <i>F</i>							
<i>4D</i> <i>2F</i>	2	6	E2	4492.40	3.080e-03	2.834e-12	3.14e-04
	4	6	E2	4500.79	1.145e-03	5.229e-13	1.16e-04
	4	8	E2	4481.05	5.222e-03	2.426e-12	4.05e-04
	6	6	E2	4500.17	2.455e-03	7.478e-13	2.48e-04
	6	8	E2	4480.43	5.838e-03	1.809e-12	4.53e-04
	8	6	E2	4468.85	1.653e-04	3.874e-14	1.73e-05
	8	8	E2	4449.39	1.050e-03	2.503e-13	8.43e-05
	4	6	M1	4500.79	5.454e-05	1.222e-11	2.69e-03
	6	6	M1	4500.17	1.577e-05	2.356e-12	7.78e-04
	6	8	M1	4480.43	2.231e-05	3.351e-12	8.36e-04
	8	6	M1	4468.85	1.593e-04	1.800e-11	8.03e-03
	8	8	M1	4449.39	7.552e-06	8.582e-13	2.89e-04
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>5</i> ² <i>S</i>							
<i>4D</i> <i>2S</i>	4	2	E2	3599.47	1.162e-04	1.042e-13	1.08e-04
	6	2	E2	3599.06	2.552e-04	1.526e-13	2.37e-04
	2	2	M1	3594.10	7.434e-06	4.179e-12	2.16e-03
	4	2	M1	3599.47	6.039e-05	1.694e-11	1.75e-02
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ² <i>D</i>							
<i>4D</i> <i>2D</i>	2	4	E2	2840.92	6.147e-08	2.247e-16	9.30e-08
	2	6	E2	2837.97	3.711e-06	1.362e-14	3.76e-06
	4	4	E2	2844.27	1.220e-05	2.220e-14	1.84e-05
	4	6	E2	2841.32	6.101e-06	1.115e-14	6.15e-06
	6	4	E2	2844.02	3.791e-05	4.599e-14	5.70e-05
	6	6	E2	2841.07	1.695e-04	2.064e-13	1.71e-04
	8	4	E2	2831.48	4.007e-06	3.705e-15	6.16e-06
	8	6	E2	2828.56	1.174e-05	1.090e-14	1.21e-05
	2	4	M1	2840.92	2.388e-03	1.698e-09	7.02e-01
	4	4	M1	2844.27	1.066e-03	3.786e-10	3.12e-01
	4	6	M1	2841.32	1.701e-03	6.048e-10	3.33e-01
	6	4	M1	2844.02	3.825e-04	9.056e-11	1.12e-01
	6	6	M1	2841.07	1.311e-03	3.108e-10	2.57e-01
	8	6	M1	2828.56	4.146e-03	7.413e-10	8.24e-01
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ² <i>G</i>							
<i>4D</i> <i>2G</i>	4	8	E2	2274.84	9.141e-06	3.262e-14	2.10e-05
	6	8	E2	2274.68	3.187e-06	7.583e-15	7.32e-06
	6	10	E2	2274.81	1.649e-04	3.912e-13	3.03e-04
	8	8	E2	2266.65	1.738e-06	3.142e-15	4.07e-06
	8	10	E2	2266.78	9.079e-06	1.636e-14	1.70e-05
	6	8	M1	2274.68	7.304e-10	2.165e-16	2.09e-07
	8	8	M1	2266.65	1.221e-08	2.725e-15	3.53e-06
	8	10	M1	2266.78	6.577e-09	1.467e-15	1.52e-06
<i>3d</i> ⁵ <i>5</i> ⁴ <i>D</i> – <i>3d</i> ⁵ <i>3</i> ² <i>P</i>							
<i>4D</i> <i>2P</i>	2	4	E2	1633.42	3.534e-07	6.801e-15	8.51e-06
	4	2	E2	1634.31	1.851e-05	1.777e-13	8.89e-04
	4	4	E2	1634.53	1.359e-05	1.304e-13	3.26e-04
	6	2</td					

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})			
$3d^5 5^4D - 3d^5 1^2D$		8	4	E2	1630.29	1.084e-05	5.252e-14	2.64e-04			
		2	2	M1	1633.21	2.922e-05	3.616e-11	9.05e-02			
		2	4	M1	1633.42	1.454e-05	1.799e-11	2.25e-02			
		4	2	M1	1634.31	1.171e-04	7.238e-11	3.62e-01			
		4	4	M1	1634.53	5.154e-06	3.186e-12	7.96e-03			
		6	4	M1	1634.44	1.793e-04	7.390e-11	2.77e-01			
$3d^5 5^2I - 3d^5 3^2I$		2	4	E2	1441.72	7.743e-06	2.168e-13	3.48e-04			
		2	6	E2	1442.06	5.363e-06	1.498e-13	1.61e-04			
		4	4	E2	1442.58	1.324e-04	1.849e-12	5.93e-03			
		4	6	E2	1442.92	1.020e-05	1.422e-13	3.04e-04			
		6	4	E2	1442.52	5.921e-05	5.513e-13	2.65e-03			
		6	6	E2	1442.86	5.050e-04	4.694e-12	1.51e-02			
		8	4	E2	1439.29	1.901e-04	1.339e-12	8.62e-03			
		8	6	E2	1439.62	1.762e-03	1.238e-11	5.32e-02			
		2	4	M1	1441.72	7.944e-07	1.114e-12	1.79e-03			
		4	4	M1	1442.58	1.990e-06	1.394e-12	4.47e-03			
		4	6	M1	1442.92	1.677e-07	1.174e-13	2.51e-04			
		6	4	M1	1442.52	5.472e-06	2.555e-12	1.23e-02			
		6	6	M1	1442.86	1.385e-05	6.464e-12	2.07e-02			
		8	6	M1	1439.62	3.316e-06	1.164e-12	5.00e-03			
$3d^5 5^2I - 3d^5 3^2F$		12	14	M1	8.40e+06	6.401e+00	1.790e-09	2.08e-08			
$3d^5 5^2I - 3d^5 3^2F$		2	2	E2	23171.75	1.030e-03	1.157e-15	2.16e-08			
$3d^5 5^2I - 3d^5 3^4F$		12	8	E2	17803.73	1.607e-04	4.015e-16	1.26e-08			
		12	10	E2	18043.70	1.193e-03	2.822e-15	6.98e-08			
		12	10	M1	18043.70	2.761e-05	5.145e-13	1.27e-05			
$3d^5 5^2I - 3d^5 3^2H$		12	10	E2	11136.23	8.665e-01	8.876e-12	5.67e-04			
		12	12	E2	10764.03	3.890e-02	4.435e-13	2.51e-05			
		14	10	E2	11151.01	2.384e-02	2.036e-13	1.55e-05			
		14	12	E2	10777.84	1.040e+00	9.897e-12	6.68e-04			
		12	10	M1	11136.23	4.189e-02	1.272e-09	8.18e-02			
		12	12	M1	10764.03	1.120e-01	3.524e-09	2.02e-01			
		14	12	M1	10777.84	6.014e-02	1.608e-09	1.08e-01			
$3d^5 5^2I - 3d^5 5^2G$		2	2	G	9681.10	1.339e-02	2.065e-13	2.20e-05			
		12	8	E2	9396.20	4.397e-02	7.458e-13	6.72e-05			
		14	10	E2	9406.72	6.312e-03	8.964e-14	9.60e-06			
		12	10	M1	9396.20	8.852e-03	3.181e-10	2.88e-02			
$3d^5 5^2I - 3d^5 5^2F$		2	2	F	7054.28	6.011e-02	2.396e-12	4.82e-04			
$3d^5 5^2I - 3d^5 3^2G$		12	8	E2	2791.84	6.024e+00	3.888e-09	4.97e+00			
		12	10	E2	2792.02	2.267e-01	1.457e-10	1.50e-01			
		14	10	E2	2792.95	7.393e+00	4.045e-09	4.87e+00			
		12	10	M1	2792.02	1.955e-07	2.360e-14	2.42e-05			
$3d^5 5^2D - 3d^5 5^2D$		2	2	D	1.96e+05	1.836e+00	7.204e-09	1.64e-03			
$3d^5 5^2D - 3d^5 3^2F$		2	2	F	47274.62	1.584e-01	5.867e-14	1.25e-07			
		4	8	E2	74471.25	3.681e-02	2.871e-15	2.25e-09			
		6	6	E2	38092.34	3.266e-03	1.698e-15	7.60e-09			
		6	8	E2	53975.28	2.931e-01	4.877e-14	8.96e-08			
		4	6	M1	47274.62	8.928e-01	1.865e-08	3.80e-02			
		6	6	M1	38092.34	9.279e-01	1.656e-08	7.55e-02			
		6	8	M1	53975.28	8.061e-01	9.842e-09	1.73e-02			
$3d^5 5^2D - 3d^5 3^4F$		2	2	F	4	4	E2	35897.62	6.909e-04	5.890e-16	3.25e-09
		4	6	E2	35886.03	2.408e-02	2.052e-14	7.55e-08			
		4	8	E2	37821.48	1.549e-04	1.074e-16	2.80e-10			
		6	4	E2	30343.49	8.416e-03	8.545e-15	9.16e-08			
		6	6	E2	30335.20	2.891e-04	2.934e-16	2.10e-09			
		6	8	E2	31706.78	1.407e-03	1.205e-15	6.15e-09			

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})			
		6	10	E2	32475.97	1.737e-04	1.349e-16	5.38e-10			
		4	4	M1	35897.62	1.144e-01	3.155e-09	1.67e-02			
		4	6	M1	35886.03	2.657e-02	7.328e-10	2.58e-03			
		6	4	M1	30343.49	2.293e-07	5.115e-15	5.53e-08			
		6	6	M1	30335.20	2.880e-01	6.424e-09	4.64e-02			
		6	8	M1	31706.78	2.183e-01	4.604e-09	2.31e-02			
$3d^5 5^2D - 3d^5 3^2H$		2	2	H	15344.95	2.905e-04	2.243e-15	3.82e-08			
$3d^5 5^2D - 3d^5 5^2G$		2	2	G	4	8	E2	13593.24	4.602e-04	7.347e-15	1.39e-07
		6	8	E2	12712.13	1.557e-03	2.090e-14	6.57e-07			
		6	10	E2	12225.39	9.187e-05	1.397e-15	3.77e-08			
		6	8	M1	12712.13	1.165e-03	6.147e-11	1.91e-03			
$3d^5 5^2D - 3d^5 5^2F$		2	2	F	4	6	E2	9004.87	6.916e-04	3.826e-14	2.18e-06
		4	8	E2	8926.18	7.359e-04	4.216e-14	1.82e-06			
		6	6	E2	8609.56	4.974e-01	2.142e-11	1.96e-03			
		6	8	E2	8537.60	6.075e-02	2.705e-12	1.87e-04			
		4	6	M1	9004.87	3.185e-03	3.530e-10	1.96e-02			
		6	6	M1	8609.56	4.479e-04	3.485e-11	3.15e-03			
		6	8	M1	8537.60	2.764e-03	2.175e-10	1.50e-02			
$3d^5 5^2D - 3d^5 5^2S$		2	2	S	4	2	E2	5999.27	9.845e-03	1.875e-12	7.09e-04
		6	2	E2	5821.20	6.244e-03	8.794e-13	5.23e-04			
		4	2	M1	5999.27	1.702e-06	2.849e-13	1.06e-04			
$3d^5 5^2D - 3d^5 3^2D$		2	2	D	4	4	E2	4158.83	5.148e-01	2.962e-10	1.16e-01
		4	6	E2	4152.53	2.204e-01	1.276e-10	3.33e-02			
		6	4	E2	4072.47	2.207e-01	9.100e-11	5.52e-02			
		6	6	E2	4066.43	5.953e-01	2.469e-10	9.99e-02			
		4	4	M1	4158.83	2.600e-07	6.291e-14	2.44e-05			
		4	6	M1	4152.53	6.525e-07	1.582e-13	4.10e-05			
		6	4	M1	4072.47	4.897e-09	8.091e-16	4.89e-07			
		6	6	M1	4066.43	1.188e-05	1.967e-12	7.94e-04			
$3d^5 5^2D - 3d^5 3^2G$		2	2	G	4	8	E2	3044.52	4.787e-01	7.076e-10	2.56e-01
		6	8	E2	2997.98	5.284e-02	5.489e-11	3.05e-02			
		6	10	E2	2998.20	4.846e-01	5.013e-10	2.24e-01			
		6	8	M1	2997.98	5.894e-07	1.325e-13	7.38e-05			
$3d^5 5^2D - 3d^5 3^2P$		2	2	P	4	2	E2	1997.02	3.919e-01	2.051e-09	6.91e+00
		4	4	E2	1997.34	3.947e-01	2.065e-09	3.48e+00			
		6	2	E2	1976.89	2.033e-01	7.341e-10	3.77e+00			
		6	4	E2	1977.20	7.321e-01	2.644e-09	6.78e+00			
		4	2	M1	1997.02	9.484e-06	4.789e-12	1.61e-02			
		4	4	M1	1997.34	3.886e-05	1.963e-11	3.29e-02			
		6	4	M1	1977.20	1.273e-05	4.336e-12	1.11e-02			
$3d^5 5^2D - 3d^5 1^2D$		2	2	D	4	4	E2	1718.01	2.966e-04	2.441e-12	5.55e-03
		4	6	E2	1718.49	1.084e-04	8.905e-13	1.35e-03			
		6	4	E2	1703.09	1.352e-01	7.642e-10	2.64e+00			
		6	6	E2	1703.56	4.868e-02	2.746e-10	6.33e-01			
		4	4	M1	1718.01	1.157e-05	6.798e-12	1.54e-02			
		4	6	M1	1718.49	4.333e-06	2.543e-12	3.84e-03			
		6	4	M1	1703.09	7.459e-06	2.950e-12	1.02e-02			
		6	6	M1	1703.56	6.677e-05	2.639e-11	6.07e-02			
$3d^5 3^2F - 3d^5 3^2F$		2	2	F	8	6	E2	1.29e+05	2.674e+00	1.132e-08	5.54e-03
$3d^5 3^2F - 3d^5 3^4F$		2	2	F	8	4	E2	69304.87	4.024e-03	2.844e-16	7.05e-10
		8	6	E2	69261.67	4.058e-02	2.866e-15	4.75e-09			
		6	4	M1	1.49e+05	1.365e+00	6.090e-09	2.77e-03			
		6	6	M1	1.49e+05	2.716e-02	1.211e-10	3.69e-05			
		6	8	M1	1.89e+05	1.861e+00	6.017e-09	9.27e-04			
		8	6	M1	69261.67	5.433e-02	4.116e-10	7.35e-04			
		8	8	M1	76852.14	1.106e-02	7.362e-11	8.22e-05			

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})	
$3d^5 \ 3^2F - 3d^5 \ 3^2H$		8	10	M1	81532.82	1.452e-01	8.925e-10	7.23e-04	
$2^2F \ 2^2H$	6	10	E2	25696.37	6.804e-03	1.096e-14	6.80e-08		
	8	10	E2	21440.36	6.425e-03	1.399e-14	1.59e-07		
	8	12	E2	20102.12	4.575e-02	1.219e-13	1.30e-06		
	8	10	M1	21440.36	1.084e-03	2.573e-11	2.97e-04		
$3d^5 \ 3^2F - 3d^5 \ 5^2G$		6	8	E2	19079.24	2.187e-06	8.501e-18	1.21e-10	
$2^2F \ 2^2G$	6	10	E2	18003.42	1.230e-03	5.761e-15	7.28e-08		
	8	8	E2	16628.42	1.012e-03	4.623e-15	1.11e-07		
	8	10	E2	15805.28	1.692e-03	9.087e-15	1.92e-07		
	6	8	M1	19079.24	3.867e-02	1.350e-09	1.88e-02		
	8	8	M1	16628.42	3.026e-02	9.202e-10	2.22e-02		
	8	10	M1	15805.28	9.549e-03	3.064e-10	6.52e-03		
$3d^5 \ 3^2F - 3d^5 \ 5^2F$		2^2F	6	E2	11123.72	9.792e-01	1.930e-11	1.07e-03	
	6	8	E2	11003.88	1.825e-01	3.755e-12	1.58e-04		
	8	6	E2	10243.49	2.688e-01	5.204e-12	4.45e-04		
	8	8	E2	10141.78	2.175e+00	4.380e-11	2.84e-03		
	6	6	M1	11123.72	2.448e-03	1.468e-10	8.00e-03		
	6	8	M1	11003.88	2.528e-02	1.537e-09	6.40e-02		
	8	6	M1	10243.49	9.986e-03	4.914e-10	4.18e-02		
	8	8	M1	10141.78	3.005e-04	1.498e-11	9.71e-04		
$3d^5 \ 3^2F - 3d^5 \ 5^2S$		$2^2F \ 2^2S$	6	2	E2	6871.25	2.273e-03	1.935e-13	8.31e-05
$3d^5 \ 3^2F - 3d^5 \ 3^2D$		$2^2F \ 2^2D$	6	4	E2	4559.98	8.280e-03	2.422e-12	1.18e-03
	6	6	E2	4552.41	2.533e-01	7.461e-11	2.42e-02		
	8	4	E2	4404.82	3.427e-02	8.416e-12	5.79e-03		
	8	6	E2	4397.75	1.208e-02	2.987e-12	1.37e-03		
	6	4	M1	4559.98	1.016e-04	1.497e-11	7.22e-03		
	6	6	M1	4552.41	1.164e-04	1.720e-11	5.55e-03		
	8	6	M1	4397.75	2.683e-04	3.086e-11	1.42e-02		
$3d^5 \ 3^2F - 3d^5 \ 3^2G$		$2^2F \ 2^2G$	6	8	E2	3254.09	9.163e-03	7.427e-12	3.52e-03
	6	10	E2	3254.34	1.349e-01	1.088e-10	4.14e-02		
	8	8	E2	3174.29	7.984e-03	5.261e-12	3.47e-03		
	8	10	E2	3174.53	8.879e-04	5.825e-13	3.08e-04		
	6	8	M1	3254.09	2.613e-06	5.409e-13	2.56e-04		
	8	8	M1	3174.29	2.446e-05	3.901e-12	2.58e-03		
	8	10	M1	3174.53	1.117e-04	1.778e-11	9.42e-03		
$3d^5 \ 3^2F - 3d^5 \ 3^2P$		$2^2F \ 2^2P$	6	2	E2	2085.10	2.541e-02	7.808e-11	3.61e-01
	6	4	E2	2085.45	1.723e-01	5.294e-10	1.22e+00		
	8	4	E2	2052.39	3.532e-02	8.573e-11	2.72e-01		
	6	4	M1	2085.45	1.019e-05	3.290e-12	7.58e-03		
$3d^5 \ 3^2F - 3d^5 \ 1^2D$		$2^2F \ 2^2D$	6	4	E2	1782.80	5.098e-01	2.510e-09	7.93e+00
	6	6	E2	1783.31	1.105e-01	5.427e-10	1.14e+00		
	8	4	E2	1758.58	1.116e-01	4.307e-10	1.86e+00		
	8	6	E2	1759.08	1.059e+00	4.078e-09	1.17e+01		
	6	4	M1	1782.80	2.446e-04	9.239e-11	2.91e-01		
	6	6	M1	1783.31	3.782e-05	1.427e-11	3.00e-02		
	8	6	M1	1759.08	4.577e-05	1.315e-11	3.78e-02		
$3d^5 \ 3^4F - 3d^5 \ 3^4F$		$4^4F \ 4^4F$	8	6	M1	7.01e+05	1.052e+01	9.655e-09	1.37e-04
	10	8	M1	1.34e+06	9.654e+00	3.933e-09	1.36e-05		
$3d^5 \ 3^4F - 3d^5 \ 3^2H$		$4^2F \ 2^2H$	6	10	E2	31053.01	3.094e-03	2.837e-15	1.20e-08
	8	10	E2	29736.24	4.089e-03	3.319e-15	1.97e-08		
	8	12	E2	27222.74	1.030e-02	1.103e-14	6.43e-08		
	10	10	E2	29090.06	1.819e-03	1.290e-15	9.78e-09		
	10	12	E2	26680.18	4.260e-02	3.956e-14	2.94e-07		
	8	10	M1	29736.24	3.737e-02	6.388e-10	3.83e-03		
	10	10	M1	29090.06	1.119e-01	1.576e-09	1.23e-02		
	10	12	M1	26680.18	2.694e-03	4.151e-11	3.19e-04		

Table A1 – continued

Multiplet	Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s^{-1})	
$3d^5 \ 3^4F - 3d^5 \ 5^2G$		4	8	E2	21877.53	3.074e-05	1.189e-16	8.59e-10	
$4^2F \ 2^2G$	6	10	E2	20478.37	1.135e-04	3.623e-16	3.53e-09		
	8	8	E2	21219.71	8.216e-05	1.789e-16	2.67e-09		
	10	8	E2	20888.60	2.489e-03	4.621e-15	8.76e-08		
	10	10	E2	19605.92	5.163e-04	1.172e-15	2.00e-08		
	6	8	M1	21881.84	3.235e-02	9.850e-10	1.04e-02		
	8	8	M1	21219.71	6.131e-02	1.456e-09	2.16e-02		
	8	10	M1	19897.33	7.078e-02	1.800e-09	2.42e-02		
	10	8	M1	20888.60	8.359e-03	1.622e-10	3.09e-03		
	10	10	M1	19605.92	1.545e-01	3.207e-09	5.53e-02		
$3d^5 \ 3^4F - 3d^5 \ 5^2F$		$4^2F \ 2^2F$	4	6	E2	12020.10	6.831e-05	1.601e-15	5.08e-08
	4	8	E2	11880.29	2.572e-05	6.316e-16	1.52e-08		
	6	6	E2	12021.40	1.808e-01	2.826e-12	1.34e-04		
	6	8	E2	11881.56	3.410e-02	5.584e-13	2.02e-05		
	8	6	E2	11818.79	4.377e-03	5.478e-14	3.54e-06		
	8	8	E2	11683.61	4.320e-02	5.659e-13	2.78e-05		
	10	6	E2	11715.36	2.576e-03	2.673e-14	2.18e-06		
	10	8	E2	11582.52	1.060e-04	1.150e-15	7.12e-08		
	4	6	M1	12020.10	4.300e-02	3.580e-09	1.11e-01		
	6	6	M1	12021.40	7.719e-03	4.284e-10	2.00e-02		
	6	8	M1	11881.56	1.205e-02	6.793e-10	2.42e-02		
	8	6	M1	11818.79	1.465e-02	6.235e-10	3.99e-02		
	8	8	M1	11683.61	1.573e-02	6.795e-10	3.33e-02		
	10	8	M1	11582.52	5.942e-02	2.077e-09	1.29e-01		
$3d^5 \ 3^4F - 3d^5 \ 5^2S$		$4^2F \ 2^2S$	4	2	E2	7203.05	6.078e-04	6.744e-14	1.76e-05
	6	2	E2	7203.52	7.719e-04	5.710e-14	2.23e-05		
	4	2	M1	7203.05	7.872e-08	1.100e-14	2.84e-06		
$3d^5 \ 3^4F - 3d^5 \ 3^2D$		$4^2F \ 2^2D$	4	4	E2	4703.78	3.121e-02	1.249e-11	3.79e-03
	4	6	E2	4695.72	1.334e-02	5.375e-12	1.09e-03		
	6	4	E2	4703.98	1.937e-02	5.169e-12	2.35e-03		
	6	6	E2	4695.92	1.053e-01	2.830e-11	8.61e-03		
	8	4	E2	4672.64	7.951e-03	1.632e-12	9.99e-04		
	8	6	E2	4664.68	4.389e-08	9.072e-18	3.71e-09		
	10	6	E2	4648.48	5.458e-02	9.154e-12	4.69e-03		
	4	4	M1	4703.78	3.048e-06	6.534e-13	1.97e-04		
	4	6	M1	4695.72	3.846e-05	8.264e-12	1.67e-03		
	6	4	M1	4703.98	2.821e-05	4.031e-12	1.83e-03		
	6	6	M1	4695.92	1.913e-05	2.741e-12	8.31e-04		
	8	6	M1	4664.68	2.724e-05	2.951e-12	1.21e-03		
$3d^5 \ 3^4F - 3d^5 \ 3^2G$		$4^2F \ 2^2G$	4	8	E2	3326.66	3.148e-02	3.585e-11	1.08e-02
	6	8	E2	3326.76	3.048e-04	2.314e-13	1.05e-04		
	6	10	E2	3327.02	8.334e-02	6.298e-11	2.29e-02		
	8	8	E2	3311.05	1.692e-02	9.809e-12	5.95e-03		
	8	10	E2	3311.31	1.331e-03	7.683e-13	3.74e-04		
	10	8	E2	3302.88	5.473e-03	2.564e-12	1.95e-03		
	10	10	E2	3303.14	7.799e-02	3.637e-11	2.22e-02		
	6	8	M1	3326.76	2.102e-06	4.257e-13	1.92e-04		
	8	8	M1	3311.05	4.790e-07	7.320e-14	4.45e-05		
	8	10	M1	3311.31	6.454e-05	9.847e-12	4.79e-03		
	10	8	M1	3302.88	6.494e-05	7.965e-12	6.08e-03		
	10	10	M1	3303.14	1.111e-05	1.360e-12	8.31e-04		
$3d^5 \ 3^4F - 3d^5 \ 3^2P$		$4^2F \ 2^2P$	4	2	E2	2114.66	2.373e-02	1.049e-10	3.14e-01
	4	4	E2	2115.02	2.392e-02	1.057e-10	1.58e-01		
	6	2	E2	2114.70	5.232e-02	1.542e-10	6.93e-01		
	6	4	E2	2115.06	6.642e-02	1.957e-10	4.39e-01		
	8	4	E2	2108.70	1.059e-02	2.368e-11	7.11e-02		
	4	2	M1	2114.66	5.576e-07	2.662e-13	7.95e-04		
	4	4	M1	2115.02	5.030e-07	2.402e-13	3.59e-04		
	6	4	M1	2115.06	1.777e-06	5.656e-13	1.27e-03		

Table A1 – continued

Multiplet	g _i	g _k	Type	λ (Å)	S	f _{ik}	A _{ki} (s ⁻¹)
$3d^5 \ _3^4F - 3d^5 \ _1^2D$							
$^4F \ ^2D$	4	4	E2	1804.36	1.149e-05	8.185e-14	1.68e-04
	4	6	E2	1804.89	5.602e-06	3.982e-14	5.46e-05
	6	4	E2	1804.39	9.662e-02	4.590e-10	1.41e+00
	6	6	E2	1804.92	2.021e-02	9.577e-11	1.97e-01
	8	4	E2	1799.76	2.568e-03	9.240e-12	3.81e-02
	8	6	E2	1800.29	1.851e-02	6.644e-11	1.83e-01
	10	6	E2	1797.87	4.254e-05	1.228e-13	4.23e-04
	4	4	M1	1804.36	2.409e-04	1.348e-10	2.76e-01
	4	6	M1	1804.89	3.203e-05	1.791e-11	2.45e-02
	6	4	M1	1804.39	3.166e-04	1.182e-10	3.63e-01
	6	6	M1	1804.92	1.071e-04	3.993e-11	8.19e-02
	8	6	M1	1800.29	7.278e-04	2.042e-10	5.61e-01
$3d^5 \ _3^2H - 3d^5 \ _3^2H$							
$^2H \ ^2H$	10	12	M1	3.22e+05	4.461e+00	5.915e-09	3.00e-04
$3d^5 \ _3^2H - 3d^5 \ _5^2G$							
$^2H \ ^2G$	10	8	E2	74090.54	2.862e+00	1.099e-13	1.79e-07
	10	10	E2	60135.91	9.165e-02	6.913e-15	1.30e-08
	12	8	E2	96227.87	1.135e-01	1.539e-15	1.93e-09
	12	10	E2	73942.62	3.485e+00	1.127e-13	1.77e-07
	10	8	M1	74090.54	7.701e-01	4.102e-09	6.38e-03
	10	10	M1	60135.91	1.533e+00	1.023e-08	1.90e-02
	12	10	M1	73942.62	9.422e-01	4.198e-09	6.29e-03
$3d^5 \ _3^2H - 3d^5 \ _5^2F$							
$^2H \ ^2F$	10	6	E2	19614.77	2.158e+00	4.627e-12	1.39e-04
	10	8	E2	19245.20	8.800e-02	2.035e-13	4.67e-06
	12	8	E2	20468.32	3.084e+00	4.881e-12	1.20e-04
	10	8	M1	19245.20	1.301e-03	2.716e-11	6.15e-04
$3d^5 \ _3^2H - 3d^5 \ _3^2D$							
$^2H \ ^2D$	10	6	E2	5532.56	4.457e-01	4.403e-11	1.61e-02
$3d^5 \ _3^2H - 3d^5 \ _3^2G$							
$^2H \ ^2G$	10	8	E2	3725.92	4.005e-02	1.301e-11	7.81e-03
	10	10	E2	3726.25	6.539e-01	2.114e-10	1.02e-01
	12	8	E2	3769.53	8.856e-02	2.312e-11	1.63e-02
	12	10	E2	3769.87	7.543e-03	1.958e-12	1.11e-03
	10	8	M1	3725.92	8.920e-04	9.685e-11	5.81e-02
	10	10	M1	3726.25	1.027e-05	1.113e-12	5.35e-04
	12	10	M1	3769.87	1.551e-05	1.383e-12	7.81e-04
$3d^5 \ _3^2H - 3d^5 \ _1^2D$							
$^2H \ ^2D$	10	6	E2	1916.30	3.023e-04	7.190e-13	2.18e-03
$3d^5 \ _5^2G - 3d^5 \ _5^2G$							
$^2G \ ^2G$	8	10	M1	3.19e+05	3.664e+00	6.162e-09	3.04e-04
$3d^5 \ _5^2G - 3d^5 \ _5^2F$							
$^2G \ ^2F$	8	6	E2	26677.34	3.785e-03	4.084e-15	5.23e-08
	8	8	E2	25998.34	6.520e-04	7.789e-16	7.68e-09
	10	6	E2	29109.54	3.107e-01	2.025e-13	2.77e-06
	10	8	E2	28302.95	3.709e-02	2.702e-14	2.86e-07
	8	6	M1	26677.34	1.329e-03	2.497e-11	3.15e-04
	8	8	M1	25998.34	2.465e-03	4.792e-11	4.73e-04
	10	8	M1	28302.95	4.305e-03	6.118e-11	6.40e-04
$3d^5 \ _5^2G - 3d^5 \ _3^2D$							
$^2G \ ^2D$	8	4	E2	5992.11	2.329e+00	2.272e-10	8.44e-02
	8	6	E2	5979.04	2.981e-01	2.933e-11	7.28e-03
	10	6	E2	6093.14	2.811e+00	2.083e-10	6.25e-02
	8	6	M1	5979.04	8.439e-06	7.139e-13	1.77e-04
$3d^5 \ _5^2G - 3d^5 \ _3^2G$							
$^2G \ ^2G$	8	8	E2	3923.21	3.051e+00	1.066e-09	4.60e-01
	8	10	E2	3923.58	3.079e-01	1.070e-10	3.71e-02
	10	8	E2	3972.02	2.367e-01	6.360e-11	3.35e-02
	10	10	E2	3972.40	3.228e+00	8.624e-10	3.65e-01
	8	8	M1	3923.21	4.581e-06	5.912e-13	2.56e-04
	8	10	M1	3923.58	5.770e-03	7.433e-10	2.58e-01
	10	8	M1	3972.02	5.150e-03	5.247e-10	2.77e-01
	10	10	M1	3972.40	3.962e-06	4.030e-13	1.71e-04
$3d^5 \ _5^2G - 3d^5 \ _3^2P$							
$^2G \ ^2P$	8	4	E2	2341.37	2.960e-03	4.840e-12	1.18e-02

Table A1 – continued

Multiplet	g _i	g _k	Type	λ (Å)	S	f _{ik}	A _{ki} (s ⁻¹)
$3d^5 \ _5^2G - 3d^5 \ _1^2D$							
$^2G \ ^2D$	8	4	E2	1966.56	7.672e-04	2.118e-12	7.30e-03
	8	6	E2	1967.18	5.908e-03	1.626e-11	3.74e-02
	10	6	E2	1979.38	1.571e-03	3.392e-12	9.65e-03
	8	6	M1	1967.18	1.327e-06	3.409e-13	7.84e-04
$3d^5 \ _5^2F - 3d^5 \ _5^2F$							
$^2F \ ^2F$	6	8	M1	1.02e+06	3.436e+00	2.971e-09	1.09e-05
$3d^5 \ _5^2S - 3d^5 \ _5^2S$							
$^2F \ ^2S$	6	2	E2	17973.97	1.176e-02	5.752e-14	3.51e-06
$3d^5 \ _5^2F - 3d^5 \ _3^2D$							
$^2F \ ^2D$	6	4	E2	7727.92	7.174e-01	4.379e-11	7.29e-03
	6	6	E2	7706.18	1.618e-01	9.988e-12	1.11e-03
	8	4	E2	7786.83	1.413e-01	6.278e-12	1.38e-03
	8	6	E2	7764.76	1.038e+00	4.667e-11	6.87e-03
	6	4	M1	7727.92	6.993e-03	6.112e-10	1.02e-01
	6	6	M1	7706.18	1.511e-02	1.325e-09	1.48e-01
	8	6	M1	7764.76	1.071e-02	6.978e-10	1.03e-01
$3d^5 \ _5^2F - 3d^5 \ _3^2G$							
$^2F \ ^2G$	6	8	E2	4599.65	8.388e-01	2.436e-10	5.70e-02
	6	10	E2	4600.15	6.956e-02	2.007e-11	3.78e-03
	8	8	E2	4620.45	1.302e-01	2.787e-11	8.66e-03
	8	10	E2	4620.97	1.097e+00	2.333e-10	5.83e-02
	6	8	M1	4599.65	3.094e-03	4.548e-10	1.07e-01
	8	8	M1	4620.45	8.311e-03	9.110e-10	2.84e-01
	8	10	M1	4620.97	3.976e-03	4.349e-10	1.09e-01
$3d^5 \ _5^2F - 3d^5 \ _3^2P$							
$^2F \ ^2P$	6	2	E2	2566.11	1.756e+00	2.912e-09	8.84e+00
	6	4	E2	2566.64	4.859e-01	8.059e-10	1.22e+00
	8	4	E2	2573.10	2.955e+00	3.639e-09	7.33e+00
	6	4	M1	2566.64	2.262e-07	5.944e-14	9.02e-05
$3d^5 \ _5^2F - 3d^5 \ _1^2D$							
$^2F \ ^2D$	6	4	E2	2123.06	8.847e-05	2.592e-13	5.74e-04
	6	6	E2	2123.79	7.140e-03	2.086e-11	3.08e-02
	8	4	E2	2127.48	1.097e-02	2.392e-11	7.05e-02
	8	6	E2	2128.22	2.555e-02	5.555e-11	1.09e-01
	6	4	M1	2123.06	2.414e-05	7.667e-12	1.70e-02
	6	6	M1	2123.79	4.681e-09	1.486e-15	2.20e-06
	8	6	M1	2128.22	9.417e-07	2.236e-13	4.39e-04
$3d^5 \ _5^2S - 3d^5 \ _3^2D$							
$^2S \ ^2D$	2	4	E2	13556.56	1.328e+00	4.476e-11	8.12e-04
	2	6	E2	13489.82	1.983e+00	6.820e-11	8.29e-04
$3d^5 \ _5^2S - 3d^5 \ _3^2P$							
$^2S \ ^2P$	2	4	E2	2994.20	1.080e-05	3.379e-14	1.26e-05
	2	2	M1	2993.48	1.592e-03	1.075e-09	8.01e-01
	2	4	M1	2994.20	7.919e-04	5.347e-10	1.99e-01
$3d^5 \ _5^2S - 3d^5 \ _1^2D$							
$^2S \ ^2D$	2	4	E2	2407.42	2.236e-03	1.346e-11	7.74e-03
	2	6	E2	2408.36	1.310e-03	7.860e-12	3.02e-03
	2	4	M1	2407.42	3.746e-06	3.146e-12	1.81e-03
$3d^5 \ _3^2D - 3d^5 \ _3^2D$							
$^2D \ ^2D$	4	6	M1	2.74e+06	2.392e+00	1.193e-09	5.23e-07
$3d^5 \ _3^2D - 3d^5 \ _3^2G$							
$^2D \ ^2G$	4	8	E2	11362.73	9.741e-04	2.829e-14	7.20e-07
	6	8	E2	11410.05	1.108e-03	2.110e-14	8.02e-07
	6	10	E2	11413.18	1.309e-03	2.452e-14	7.57e-07
	6	8	M1	11410.05	9.768e-06	5.791e-13	2.22e-05
$3d^5 \ _3^2D - 3d^5 \ _3^2P$							
$^2D \ ^2P$	4	2	E2	3841.81	3.233e-03	2.391e-12	2.16e-03
	4	4	E2	3842.99	7.156e-04	5.292e-13	2.39e-04
	6	2	E2	3847.20	1.816e-03	8.902e-13	1.21e-03
	6	4	E2	3848.39	3.957e-02	1.940e-11	1.31e-02
	4	2	M1	3841.81	1.973e-06	5.190e-13	4.69e-04
	4	4	M1	3842.99	4.560e-06	1.200e-12	5.42e-04
	6	4	M1	3848.39	2.281e-05	3.993e-12	2.70e-03
$3d^5 \ _3^2D - 3d^5 \ _1^2D$							
$^2D \ ^2D$	4	4	E2	2927.25	7.813e-01	1.308e-09	1.02e+00

Table A1 – continued

Multiplet Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s $^{-1}$)
	4	6	E2	2928.64	3.358e-01	5.599e-10	2.91e-01
	6	4	E2	2930.39	3.209e-01	3.566e-10	4.16e-01
	6	6	E2	2931.78	1.337e+00	1.480e-09	1.15e+00
	4	4	M1	2927.25	3.262e-08	1.127e-14	8.77e-06
	4	6	M1	2928.64	2.984e-03	1.029e-09	5.34e-01
	6	4	M1	2930.39	2.949e-03	6.780e-10	7.90e-01
	6	6	M1	2931.78	3.794e-10	8.713e-17	6.77e-08
$3d^5$	${}_3^2G - {}_3d^5$	${}_3^2G$					
2G	2G	10	${}_8M1$	4.17e+07	4.434e+00	8.449e-10	2.07e-10
$3d^5$	${}_3^2G - {}_3d^5$	${}_3^2P$					
2G	2P	8	${}_4E2$	5806.96	9.074e-03	9.649e-13	3.85e-04
$3d^5$	${}_3^2G - {}_3d^5$	${}_1^2D$					
2G	2D	8	${}_4E2$	3943.06	4.924e+00	1.678e-09	1.45e+00
		8	${}_6E2$	3945.58	5.402e-01	1.831e-10	1.05e-01
		10	${}_6E2$	3945.21	6.844e+00	1.866e-09	1.34e+00
		8	${}_6M1$	3945.58	6.264e-10	8.004e-17	4.58e-08

Table A1 – continued

Multiplet Terms	g_i	g_k	Type	λ (Å)	S	f_{ik}	A_{ki} (s $^{-1}$)
$3d^5$	${}_3^2P - {}_3d^5$	${}_1^2D$					
2P	2D	2	${}_4E2$	12296.64	2.062e+00	9.350e-11	2.05e-03
		2	${}_6E2$	12321.19	1.377e+00	6.147e-11	9.05e-04
		4	${}_4E2$	12284.56	2.038e+00	4.623e-11	2.04e-03
		4	${}_6E2$	12309.06	4.802e+00	1.072e-10	3.17e-03
		2	${}_4M1$	12296.64	5.706e-03	9.395e-10	2.07e-02
		4	${}_4M1$	12284.56	1.819e-02	1.498e-09	6.62e-02
		4	${}_6M1$	12309.06	1.025e-02	8.398e-10	2.47e-02
$3d^5$	${}_1^2D - {}_3d^5$	${}_1^2D$					
2D	2D	6	${}_4M1$	6.17e+06	2.387e+00	6.970e-10	6.85e-08

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